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A review of the radiolarian faunas in the Bangong-Nujiang Suture Zone: Implications for the tectonic evolution of the Mesotethys Ocean

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Abstract

The Bangong-Nujiang Suture Zone in the Qinghai-Tibet Plateau marks the evolution of the Mesotethys Ocean, which has been the subject of considerable debate regarding its opening time, evolutionary pattern, and closing process. This suture zone consists of three ophiolitic mélange zones, with their evolution and relationships far from being fully understood. As an important microfossil in deep-sea sedimentation, radiolarian plays an irreplaceable role in revealing the development timeline of oceanic basins and palaeogeographic reconstructions. This paper is designed to review the existing radiolarian records in the Bangong-Nujiang Suture Zone with the purpose of constraining the evolution of the Mesotethys Ocean. The radiolarian faunas in the Bangong-Nujiang Suture Zone suggest that the Mesotethys Ocean must have opened before the Middle Triassic according to the record of Anisian radiolarians. At the same time, the Beila-Nagqu Ocean, a branch of the Mesotethys Ocean, should have already opened. The presence of diverse Jurassic and Cretaceous radiolarians in the Shiquanhe-Namtso mélange zone confirms that the Mesotethys Ocean was still a broad oceanic basin during the Early Cretaceous. Many similar radiolarian assemblages were found in the western section of the Bangong-Nujiang Suture Zone and the Yarlung-Tsangpo Suture Zone, suggesting a connection between the Mesotethys and Neotethys oceans during that time.

Keywords: Bangong-Nujiang Suture Zone, Mesotethys Ocean, radiolarian

Introduction

The Tethyan Orogen is a giant orogenic belt across Eurasia and Asia, recording the evolution of the giant ocean between Laurasia in the north and Gondwana in the south during the Phanerozoic (Wu *et al*., 2020). The Qinghai-Tibet Plateau (QTP) is an extremely complex and key area in the Tethyan Orogen. It records the complex evolution of the Tethyan Ocean in multiple stages (Pan *et al*., 2012; Zhu *et al*., 2013; Ding *et al*., 2022; Zhu *et al*., 2022), resulting in multiple suture zones in the QTP (from north to south): Jinsha River Suture Zone (JSSZ), Longmu Co-Shuanghu Suture Zone (LSSZ), Bangong-Nujiang Suture Zone (BNSZ) and Yarlung-Tsangpo Suture Zone (YTSZ) (Fig.1).

Among them, a large number of studies have confirmed that the LSSZ can be connected to the Changning-Menglian Suture Zone in Yunnan, the Chanthaburi Suture Zone in Thailand and the Bentong-Raub Suture Zone in Malaysia, recording the evolution of the Palaeotethys Ocean (Li *et al*., 2016; Metcalfe, 2021; Li *et al*., 2024). It has been suggested that the YTSZ is linked to the Zagros Suture Zone in Iran to the west and the India-Myanmar Suture Zone to the east, recording the long evolution of the Neotethys Ocean (Wu *et al*., 2020; Zhu *et al*., 2022). However, what is special about the QTP is the existence of another important suture zone, the BNSZ, which separates the South Qiangtang Block in the north and the Lhasa Block in the south (Pan *et al*., 1983; Yin & Harrison, 2000; Zhu *et al*., 2013; Kapp & DeCelles,

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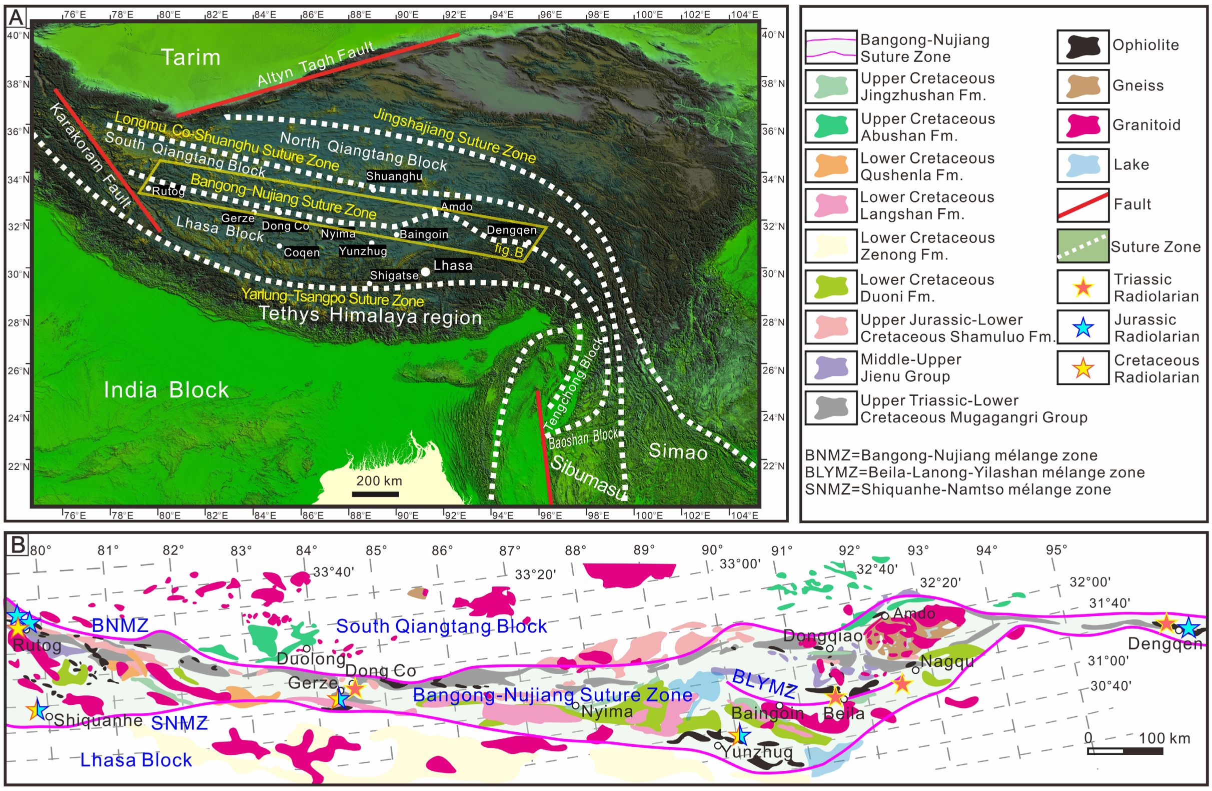

FIGURE 1. Tectonic subdivision of the QTP and the position of radiolarians in the BNSZ. **A**, Tectonic subdivision of the Qinghai-Tibet Plateau (modified from Zhang *et al*., 2019). **B**, Simplified geological map showing the Mesozoic strata within the BNSZ and surrounding areas (modified from Zhu *et al*., 2016) and the location of reported radiolarian faunas in the BNSZ.

2019; Hu *et al*., 2022). The ocean basin represented by this suture zone was named the Mesotethys Ocean or Bangong-Nujiang Ocean (BNO) (Zhang *et al*., 2019; Metcalfe, 2021; Xu *et al*., 2022; Shen *et al*., 2024). Due to the lack of extensive ophiolite exposures in the Karakoram and Pamirs in the western part of the QTP, as well as in western Yunnan and the Shan Plateau of Myanmar in the eastern part of the QTP, the lateral tracking of the BNSZ has become extremely difficult. Consequently, this suture zone is also considered to be the remnants of a branch of the Neotethys Ocean (Wu *et al*., 2020) or alternatively a branch of the Palaeotethys Ocean (Pan *et al*., 2012).

In any case, it is undeniable that the BNSZ is a complex and important tectonic belt on the QTP, which has received widespread attention in recent years due to its extremely complex tectonic evolution (Zhang *et al*., 2019; Hu *et al*., 2022; Shen *et al*., 2024). Existing research has revealed that it develops several ophiolite belts and associated mélange belts from west to east, which can be spatially subdivided into the Bangong-Nujiang mélange zone (BNMZ) in the north and the Shiquanhe-Namtso mélange zone (SNMZ) in the south, and the Beila-Lanong-Yilashan mélange zone (BLYMZ) between BNMZ and SNMZ in the Nagqu area (Tang *et al*., 2018, 2021; Zeng *et al*., 2018). Many ophiolites are irregularly distributed, resulting in different explanations regarding the Palaeogeographic reconstruction of the Mesotethys Ocean. The opening of this ocean was variously considered to be Early Palaeozoic (Pan *et al*., 2012); Early Permian (Zhang *et al*., 2019; Xu *et al*., 2022; Fan *et al*., 2024; Shen *et al*., 2024; Zhang *et al*., 2024), Jurassic (Baxter *et al*., 2009) or after Late Triassic (Wu *et al*., 2019). Similarly, the closing time of this ocean is also a hotly debated issue. For example, the first opinion suggests that the Mesotethys Ocean closed in the Late Jurassic–Early Cretaceous (*e.g*., Girardeau *et al*., 1984; Ma *et al*., 2017); the other opinion, however, suggests that the closure of this ocean was later than the Early Cretaceous (Fan *et al*., 2014, 2023; Zeng *et al*., 2021).

Radiolarian fossils are almost the only microfossils preserved in deep-water environments below the carbonate compensation depth (CCD) (Boltovskoy *et al*., 2017). They serve as significant records for tracing deep-water environment. Despite wide documentation of radiolarians in the YTSZ that have helped to reconstruct the evolution of the Neotethys Ocean (*e.g*., Li *et al*., 2013, 2019; Chen *et al*., 2019; Cui *et al*., 2021), the radiolarian faunas within the BNSZ are fairly limited. So far, the radiolarian faunas have been only reported in the Rutog and Dengqen areas in the BNMZ, in the Nagqu-Beila area in the BLYMZ and in the Lagkor Co and Yunzhug areas in the SNMZ.

This paper summarises the radiolarian records in the BNSZ for the first time with the purpose of reconstructing the evolution of the Mesotethys Ocean as well as stimulating future research directions.

Geological setting

The QTP is the highest and largest plateau on earth. It was formed by the successive breakup and northward drift of diverse blocks from the northern margin of Gondwana in the south, and subsequent accretion of those blocks to Laurasia in the north (Yin & Harrison, 2000; Pan *et al*., 2012; Wu *et al*., 2020; Ding *et al*., 2022). Tectonically, the QTP is composed of multiple blocks from north to south, including the North Qiangtang Block (or Qamdo Block), the South Qiangtang Block, the Lhasa Block and the Tethys Himalaya terrane on the northern margin of the Indian Plate, which are divided by the LSSZ, BNSZ and YTSZ respectively.

The LSSZ marks the evolution of the Palaeotethys Ocean. The opening time of this ocean was considered as Late Devonian or earlier in the Early Palaeozoic (Zhai *et al*., 2016; Li *et al*., 2024; Liang *et al*., 2024). Its closure is marked by the collision between the South Qiangtang Block and North Qiangtang Block and subsequent high-pressure metamorphism along the LSSZ during the Middle and Late Triassic (Liang *et al*., 2012; Zhai *et al*., 2017).

The YTSZ marks the evolution of the Neotethys Ocean. The opening of this ocean was variously constrained to be Middle Triassic (Chen *et al*., 2019), Late Triassic (Metcalfe, 2013; Wu *et al*., 2020), Early Triassic (Liu *et al*., 2023), or prior to the Middle Permian (Zhang *et al*., 2013, 2019, 2023; Xu *et al*., 2019; Ju *et al*., 2022; Shen *et al*., 2024). The closing of this ocean is represented by the collision of the Tethys Himalaya terrane with the Lhasa Block in the early Cenozoic (Hu *et al*., 2015; Ding *et al*., 2022; Li *et al*., 2023).

The BNSZ, the focus of the current study, is located between the South Qiangtang Block in the north and the Lhasa Block in the south. It is different from the LSSZ and YTSZ in that it has three different ophiolitic mélange zone, respectively Bangong-Nujiang mélange zone (BNMZ), Beila-Lanong-Yilashan mélange zone (BLYMZ) and Shiquanhe-Namtso mélange zone (SNMZ) from north to south (Wang *et al*., 2016; Tang *et al*., 2021).

The ophiolite belts in the BNMZ include, from west to east, Dong Co ophiolite (Bao *et al*., 2007; Wang *et al*., 2016; Li *et al*., 2019), Dongqiao-Amdo ophiolite (Liu *et al*., 2016; Wang *et al*., 2016) and Dengqen ophiolite (Qiangba *et al*., 2009; Wang *et al*., 2016). The BNMZ is characterised by different fragments (including ophiolites and oceanic islands) and thick flysch sediments. Ophiolitic rocks were mainly formed in the Jurassic (Girardeau *et al*., 1984; Shi, 2007; Sun *et al*., 2011), with the local exception of Dong Co which formed in the Early Cretaceous (132 Ma; Bao *et al*., 2007). Widespread accretionary complexes in the BNMZ are characterised by the Mugagangri Complex, which is dominated by semi-abyssal to abyssal flysch together with ophiolites, oceanic islands and allochthonous blocks (Zeng *et al*., 2016; Fan *et al*., 2018).

The ophiolite belts in the SNMZ are composed of the Shiquanhe ophiolite (Shi, 2007; Wang *et al*., 2016), the Lagkor Co ophiolite (Li *et al*., 2019), the Asa ophiolite (Zeng *et al*., 2018) and the Yunzhug ophiolite (Zhong *et al*., 2015; Zeng *et al*., 2018) from west to east. Most scholars interpreted the SNMZ as a back-arc basin due to the southward subduction of the BNO within the Lhasa arc (Xu *et al*., 2014; Zeng *et al*., 2018).

Between BNMZ and SNMZ, there is another BLYMZ in the Siling Co-Baingoin area in the middle part of the BNSZ (Tang *et al*., 2018, 2021). There exposed scatter outcrops of Upper Palaeozoic strata between the BLYMZ and BNMZ, which were named the Dongkaco microcontinent (Hu *et al*., 2022; Ma *et al*., 2024). Latest studies suggest a Lhasa Block origin for the Dongkaco microcontinent and further suggest that it collided with the South Qiangtang Block prior to the main Lhasa Block (Hu *et al*., 2022; Ma *et al*., 2024).

Material and methods

The radiolarians summarised in this study were collected from references published so far in the Bangong-Nujiang Suture Zone. Age assignment based on radiolarian faunas were classified into different mélange zones within the BNSZ, including the Bangong-Nujiang mélange zone (BNMZ), Beila-Lanong-Yilashan mélange zone (BLYMZ) and Shiquanhe-Namtso mélange zone (SNMZ) (Fig. 2). Scanning electron micrographs of characteristic radiolarian species were collected from literatures and illustrated (Fig. 3). Also, some materials from western part of the BNSZ were collected by our fieldwork in Tibet in recent years. Samples were processed with standard radiolarian extraction techniques (hydrofluoric acid method), as described by Pessagno and Newport (1972).

Results

Radiolarian faunas in the Bangong-Nujiang Suture Zone

The radiolarian faunas have been so far reported from different areas in the BNSZ. There are no reports of

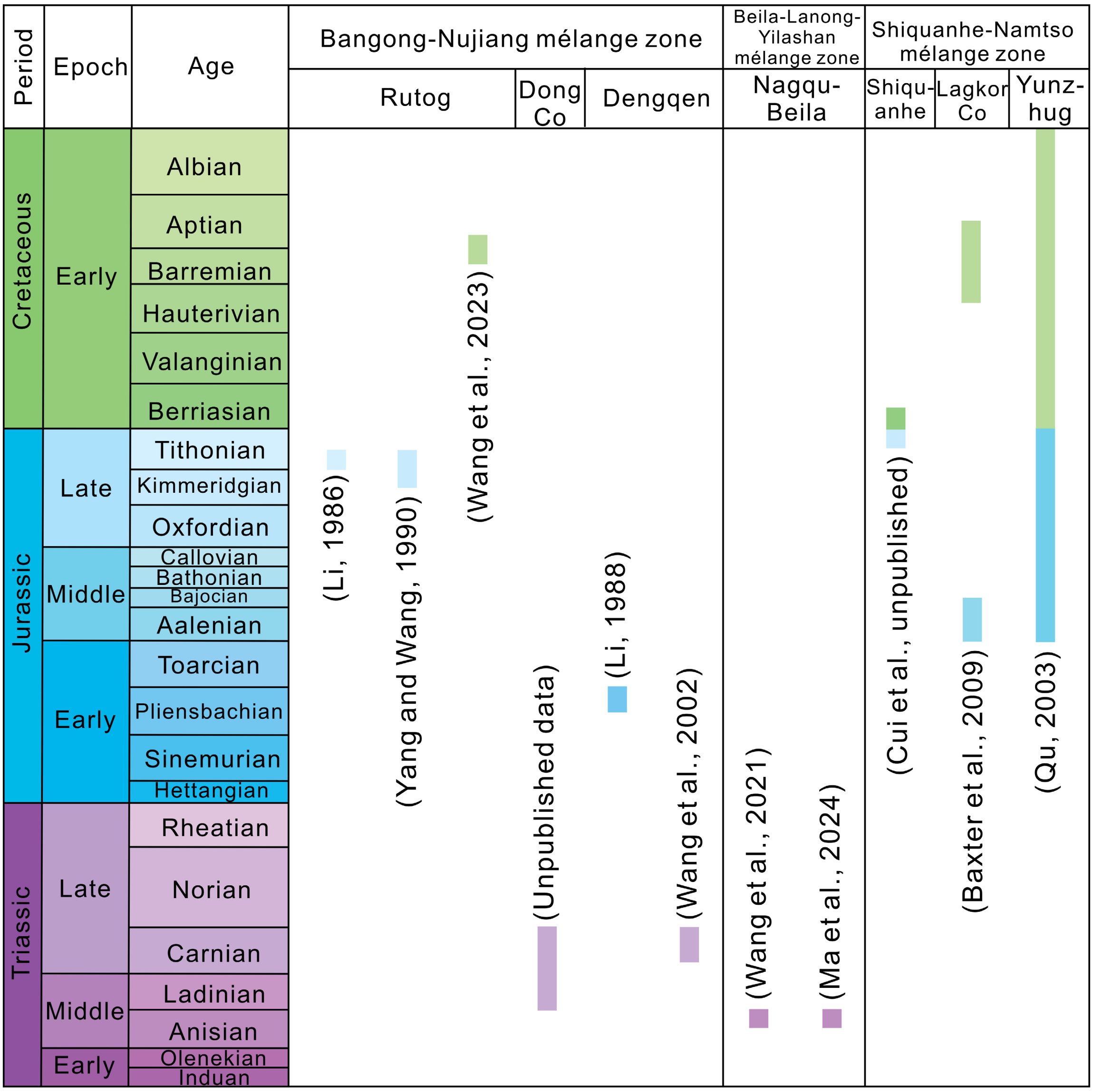

FIGURE 2. Summarising the radiolarian ages in different mélange zones in the BNSZ.

pre-Triassic and post-Cretaceous radiolarians. So, the Mesozoic radiolarians, ranging from Middle Triassic to Early Cretaceous, are summarised below (Fig. 2).

Triassic

The Triassic radiolarians were documented from the Dongco and Dengqen areas of the BNMZ and the Nagqu and Beila areas of the BLYMZ.

In the Nagqu area, Nyima & Xie (2005) documented a sequence containing Middle Triassic radiolarian fossils originally belonging to the Middle and Upper Jurassic Lagongtang Formation in the south of Gajia Village on the west side of Nagqu County, and established the Gajia Formation. The Gajia Formation is sandwiched in the Lagongtang Formation in the form of fault blocks. Its main lithology is quartz sandstone, siltstone, radiolarian argillaceous siliceous rock, conglomerate, sandy debris and brecciated limestone, as well as multiple volcanic rock interlayers, with a total thickness of more than 700 meters. One of the thin layers of grey-green siliceous rock contains abundant radiolarians including *Oertlispongus inaequispinosus* Dumitrica, Kozur & Mostler, *Baumgartneria ambigua* Dumitrica, *Pseudostylosphaera* sp. and *Muelleritortis* sp. This assemblage was initially identified as a Ladinian age of Middle Triassic. However, this age assignment was updated by the later study of Wang *et al.* (2021). Wang *et al.* (2021) conducted a systematic study on this radiolarian fauna. The radiolarian fauna was included into the *Oertlispongus inaequispinosus* assemblage (Fig. 3). The *Oertlispongus inaequispinosus* fauna is widely distributed in the world, both in the Tethyan realm and the Pacific Rim realm (*e.g.*, Goričan & Buser, 1990; Kozur & Mostler, 1994; Kozur *et al.*, 1996; Feng *et al.*, 2009; Chen *et al.*, 2019). This radiolarian assemblage

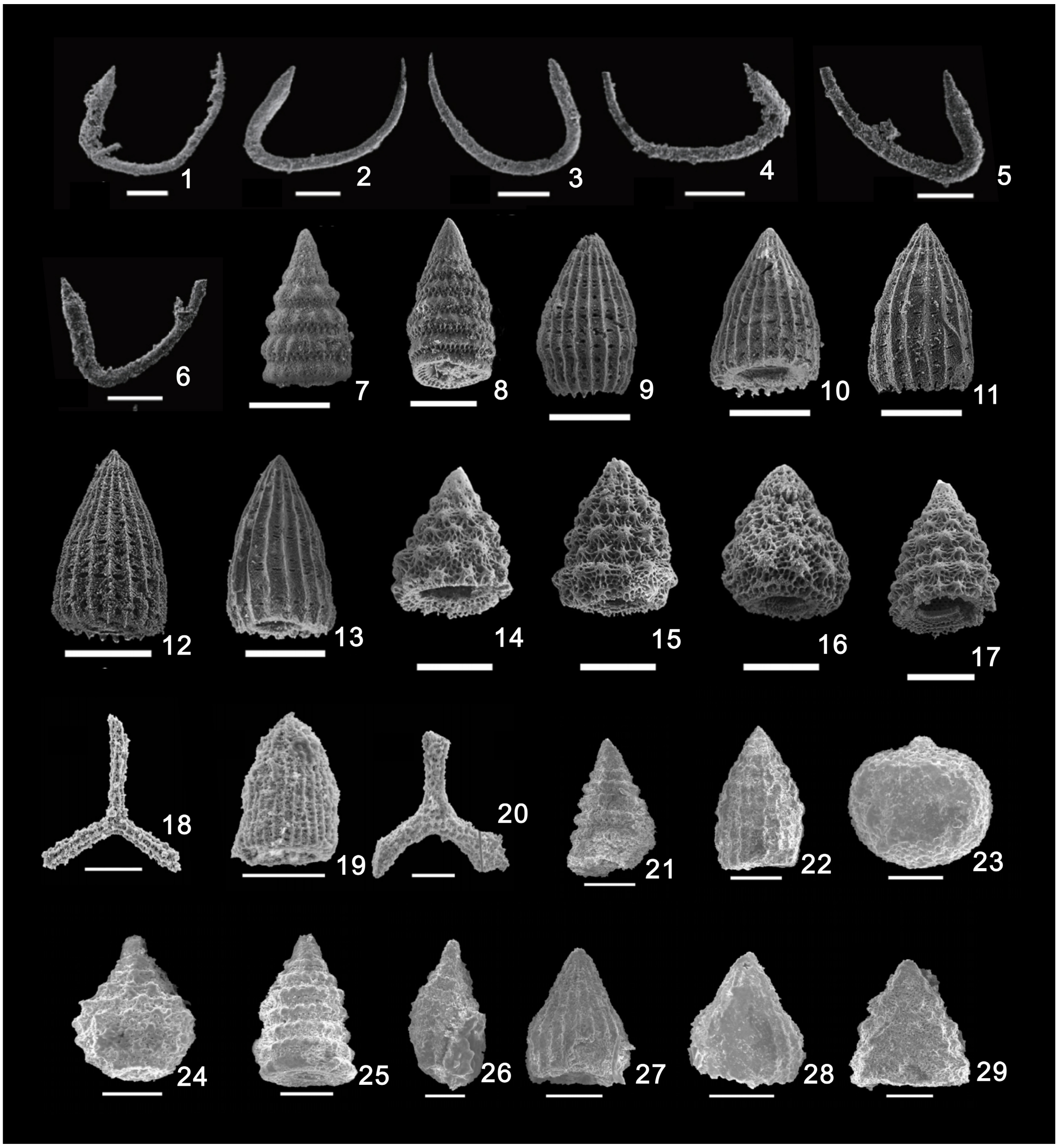

FIGURE 3. Characteristic radiolarians from the BNSZ. **1**–**6**, from the Nagqu area in BLYMZ and identified as late Anisian (Wang *et al*., 2021); **7**–**17**, from the Rutog area in BNMZ and identified late Barremian to early Aptian (Wang *et al*., 2023); **18**–**20**, from the Lagkor Co area in SNMZ and identified as early Aalenian to middle Bajocian (Baxter *et al*., 2009); **21**–**29**, from the Lagkor Co area in SNMZ and identified as latest Hauterivian to early Aptian (Baxter *et al*., 2009).**1**–**6**, *Oertlispongus inaequispinosus* Dumitrica; **7**–**8**, *Pseudodictyomitra hornatissima* (Squinabol); **9**–**13**, *Thanarla brouweri* (Tan); **14**–**17**, *Xitus clava* (Parona); **18**, *Archaeotritabs hattori* Dumitica; **19**, *Parashuum* sp. cf. *P. izense* (Pessagno & Whalen); **20**, *Crolanium puga* (Schaaf); **21**, *Dictyomitra communis* (Squinabol); **22**, *Sethocapsa orca* (Foreman); **23**, *Tethysetta usotanensis* (Tumanda); **24**, *Pseudodictyomitra carpatica* (Lozyniak); **25**, *Pseudoeucyrtis apochrypha* O'Dogherty; **26**, *Thanarla brouweri* (Tan); **27**, *Thanarla pacifica* (Tan); **28**, *Xitus clava* (Parona); **29**, *Paronaella* sp. cf. *P. skowkonaensis* Carter. Scale bar=100 μm.

was widely considered to locate below the radiolarian *Ladinocampe multiperforata* zone and *Ladinocampe vicentinensis* subzone established by Kozur & Mostler (1994) and Kozur *et al*. (1996). Both zones are close to the level of ammonite *Eoprotrachyceras curiongii*, which has been designated as the index species defining the base of the Ladinian stage (Brock *et al*., 2005). Consequently, the *Oertlispongus inaequispinosus* fauna is becoming one of the main standard fossils for determining the late Anisian strata of the Middle Triassic. Therefore, the radiolarian in the Nagqu area, originally identified as early Ladinian, was reassigned to late Anisian (Wang *et al*., 2021).

In the Beila area, Ma *et al*. (2024) also discovered a well-preserved radiolarian fauna from the cherts in the Luobuqing section within the BLYMZ. The radiolarian cherts coexist with ultramafic rocks, gabbro pods and basalts. The radiolarians are dominated by *Triassocampe* cf. *T. scalaris* Dumitrica, Kozur & Mostler, *T.* cf. *T. deweveri* Nakaseko & Nishimura, *T. baloghi* Kozur & Mostler, *T*. sp., *Pseudostylosphaera acrior* Bragin, *P. imperspicua* Bragin, *P. coccostyla* Rüst and *Eptingium japonicum* Nakaseko & Nishimura, indicating a Middle Triassic age (244–242 Ma). Both Triassic radiolarians from the Nagqu and Beila areas belong to the BLYMZ.

In the Dengqen ophiolite in the eastern BNMZ, Wang *et al*. (2002) identified the radiolarians from the purple radiolarian siliceous rocks. The radiolarian fauna is dominated by *Annulotriassocampe sulovensis* Kozur & Mock, *Capnuchosphaera triassica* De Wever, *C. theloides* De Wever, *Palaeosaturnalis triassicus* Kozur & Mock, *Perispongidium tethyus* De Wever and *Spongostylus toltilis* Kozur & Mostler, which was named *Capnuchosphaera triassic* assemblage (Wang *et al*., 2002). A correlation of biostratigraphy with contemporaneous faunas in Japan, North America and YTSZ in the QTP suggests a Carnian age of Late Triassic for the *Capnuchosphaera triassica* assemblage.

In the western part of the BNMZ, our unpublished data show that late Middle Triassic–Late Triassic radiolarian fauna is also present in the Dong Co area, including *Capnuchosphaera triassica* De Wever, *Pseudostylosphaera nazarovi* Kozur & Mostler, *Muelleritortis expanse* Kozur & Mostler, *Triassocampe sulovensis* Kozur & Mock and *Ditortis recskensis* Kozur (unpublished data).

Overall, the Triassic radiolarians in the BNSZ are limited in the BLYMZ and BNMZ. However, no Triassic radiolarians have been reported in the SNMZ so far.

Jurassic

Jurassic radiolarian faunas are relatively abundant compared to Triassic records in the BNSZ. They have been documented in the Dengqen and Rutog areas in the BNMZ, and near Lagkor Co, Yunzhug, and Shiquanhe areas in the SNMZ.

In the eastern BNMZ, Li (1988) reported radiolarian fossils from the ophiolites in Zongbai County of Dengqen. The radiolarian cherts were sandwiched between Triassic–Jurassic slate and Cretaceous shale. The fauna consists mainly of *Praeconocaryomma media* Pessagno & Poisson, *Canutus izeensis* Pessagno & Whalen and *Bagotum modesium* Pessagno & Whalen, suggesting a late Pliensbachian (Early Jurassic) age (Li, 1988).

In the western BNMZ, Li (1986) documented radiolarians in the north of Rutog County. The radiolarian cherts are sandwiched between basic volcanic rocks and tuffs. The radiolarians mainly contain *Mirifusus baileyi* Pessagno, *Parvicingula altissima* Pessagno, *P. hsui* Pessagno and *Napora bukryi* Pessagno, which corresponds to the *Mirifusus baileyi* subzone in California. This radiolarian fauna suggests an early Tithonian age of the Late Jurassic. Subsequently, Yang & Wang (1990) also reported radiolarian fossils from the cherts in the Mugagangri Complex in the south of Rutog County. The radiolarians are composed mainly of *Mirifusus guadalulupensis* Pessagno, *Tripocyclia jonesi* Pessagno and *Hsuum maxwelli* Pessagno, suggesting a late Kimmeridgian or early Tithonian age of Late Jurassic.

In the SNMZ, the radiolarian faunas have been only reported near the Lagkor Co and Yunzhug areas. In the Lagkor Co area, Baxter *et al*. (2009) discovered three radiolarian-bearing siliceous samples in the ophiolite. Two samples yield Jurassic radiolarians, which contain *Archaeotritabs hattori* Dumitica, *Paronaella* sp. cf. *P. skowkonaensis* Carter and *Parashuum izense* Pessagno & Whalen (Fig. 3). Those species suggest an early Aalenian to middle Bajocian age of the Middle Jurassic. In the Yunzhug area, Qu *et al*. (2003) documented radiolarians from the grey cherts in the Yunzhug ophiolites in southern Guomang Lake. The radiolarians consist of *Crucella* sp., *Paronaella* sp., *Archaeospongoprunum* sp. and *Orbiculiforma* sp., suggesting a Middle Jurassic to Early Cretaceous age (Qu *et al*., 2003). But the faunas were not illustrated. Recently, Cui *et al*. (unpublished) has discovered a well-preserved Late Jurassic–Early Cretaceous radiolarian chert samples from the Shiquanhe area that belongs to the SNMZ. They are dominated by *Spumellaria* (about 60% of all specimens) and representatives of the genera *Acaeniotyle*, *Dicerosaturnalis*, *Emiluvia* and *Triactoma*. Those radiolarian species overall indicate a late Tithonian–early Berriasian age.

Cretaceous

In the BNSZ, Cretaceous radiolarian records are documented in the Rutog area in BNMZ and near Lagkor Co, Yunzhug, and Shiquanhe areas in SNMZ.

In the SNMZ, Baxter *et al*. (2009) found a sample LTO703 in the Lagkor Co ophiolite, which contains abundant radiolarians, respectively *Crolanium puga* Schaaf, *Dictyomitra communis* Squinabol, *Sethocapsa orca* Foreman, *Tethysetta usotanensis* Tumanda, *Pseudodictyomitra carpatica* Lozyniak, *Pseudoeucyrtis apochrypha* O'Dogherty, *Thanarla brouweri* Tan, *T. pacifica* Tan and *Xitus clava* Parona (Fig. 3). Those species indicate a latest Hauterivian to early Aptian age of Early Cretaceous.

In BNMZ, Wang *et al.* (2023) obtained well-preserved radiolarians from the grey-green chert and brown-red radiolarian rocks in the Mugagangri Complex from three different localities in Rutog County. The radiolarians contain special species for age assignment (Fig. 3), such as *Cryptamphorella clivosa* Aliev, *Parvicingula boesii* Parona, *Pantanellium lanceola* Parona and *Xitus normalis* Wu & Li in sample HF107-3, *Dictyomitra communis* Squinabol, *Thanarla brouweri* Tan, *Archaeodictyomitra mitra* Dumitrica in sample HF109-16, *Archaeospongoprunum patricki* Jud, *Xityus clava* Parona and *Triactoma hybum* Foreman in sample HF210. Those radiolarian species broadly correspond to an Early Cretaceous age.

Discussion

Although the radiolarian records in the BNSZ have been less documented compared to the flourished studies in the YTSZ, the combination of existing studies of radiolarian faunas with those from other disciplines, such as stratigraphy, magmatism and palaeomagnetism, provides constraints on key scientific issues circling around the tectonic evolution of the Mesotethys Ocean. The opening time of the Mesotethys Ocean, the rifting of the Dongkaco microcontinent and the closure of the Mesotethys Ocean are discussed below.

The opening time of the Mesotethys Ocean

The opening time of the Mesotethys Ocean in the QTP has been an ongoing controversial scientific issue. Some scholars believed that the Mesotethys Ocean was a short-lived ocean that opened in the Early Jurassic and closed in Early Cretaceous (Baxter *et al*., 2009). Moreover, this opinion is similar to that of Wu *et al*. (2019), who suggested that the South Qiangtang Block and the Lhasa Block were adjoined together without an ocean between them during the Late Triassic. Another opinion suggests, however, that the Mesotethys Ocean was a giant ocean that existed since the Early Palaeozoic (Pan *et al*., 2012). In recent years, most scholars have suggested that the opening of this ocean occurred in the Early Permian (Zhang *et al*., 2019, 2023; Hu *et al*., 2022; Fan *et al*., 2024; Shen *et al*., 2024).

The provenance studies have suggested that the Dongkaco microcontinent has a palaeogeographic affinities with the Lhasa Block in the south (Hu *et al*., 2022; Ma *et al*., 2024). In such framework, the Mesotethys Ocean may open along the BNMZ in the north. Thus, radiolarians within the BNMZ provide key constraints on the opening of the Mesotethys Ocean. As has been documented above, *Capnuchosphaera triassica* assemblage in the Dengqen ophiolite in eastern BNMZ suggests a Carnian age of Late Triassic (Wang *et al*., 2002). Also, our unpublished data from the Dong Co area in the western part of the BNMZ proved the presence of *Capnuchosphaera triassica* assemblage. The contemporaneous appearance of the Late Triassic radiolarians from the BNMZ confirmed the presence of deep-water ocean during this time. This has weakened the opinion that there is no Mesotethys Ocean during the Late Triassic suggested by Wu *et al*. (2019).

Conversely, the presence of deep-water ocean is consistent with the opinion that the Mesotethys Ocean opened during the Early Permian time. For example, the stable Permian sequences in the Lhasa Block contrast with the varied sequences in the South Qiangtang Block (Zhang *et al*., 2019, 2023; Shen *et al*., 2024). Also, the Permian palaeobiogeography between the South Qiangtang Block and the Lhasa Block has substantial differences (Xu *et al*., 2022; Yuan *et al*., 2022; Ju *et al*., 2024). From the viewpoint of sedimentology, Fan *et al*. (2024) suggest that the Lagar Formation to Xiala Formation marks a transition from passive margin to active margin. This has been invoked to indicate an Early to Middle Permian opening time for the Mesotethys Ocean. Moreover, latest research on Permian strata in the South Qiangtang Block confirmed that the Mesotethys Ocean opened during the Artinskian time as evidenced by a shift from rifting to post-rifting sedimentary facies in the western part of the South Qiangtang Block (Zhang *et al*., 2024). These lines of evidence based on stratigraphy, sedimentology and palaeobiogeography together suggest that the Mesotethys Ocean has opened during the Early Permian time.

Taking the radiolarian records into account, it is inferred that the Mesotethys Ocean initially opened during the Early Permian, and it has become a wide ocean to allow for the deposition of deep-water sea to host radiolarians during the Triassic (Fig. 4A). This conclusion is supported by palaeomagnetic studies as well. For example, the Lhasa Block is located at 16.5° to 18.4° in the southern hemisphere during the Triassic time (Zhou *et al*., 2016). By contrast, the South Qiangtang Block was in 34.4° in the northern hemisphere (Ma *et al*., 2024). A wide Mesotethys Ocean is envisaged during the Late Triassic time.

Rifting of the Dongkaco microcontinent

The area around Baingoin is the widest area in the BNSZ, where three ophiolite zones are developed in this region, respectively Dongqiao ophiolites (BNMZ) in the north, Beila ophiolite (BLYMZ) in the middle and Yunzhug ophiolites (SNMZ) in the south. Several Lower Palaeozoic and Upper Palaeozoic strata were outcropped in the area between BLYMZ and BNMZ, and were named Dongkaco microcontinent (Hu *et al*., 2022). The origin of this microcontinent has been an unresolved puzzle. Wu *et al*. (2019) suggest that the Permian–Triassic strata in this block has no differences from the South Qiangtang Block in the north and the Lhasa Block in the south. By

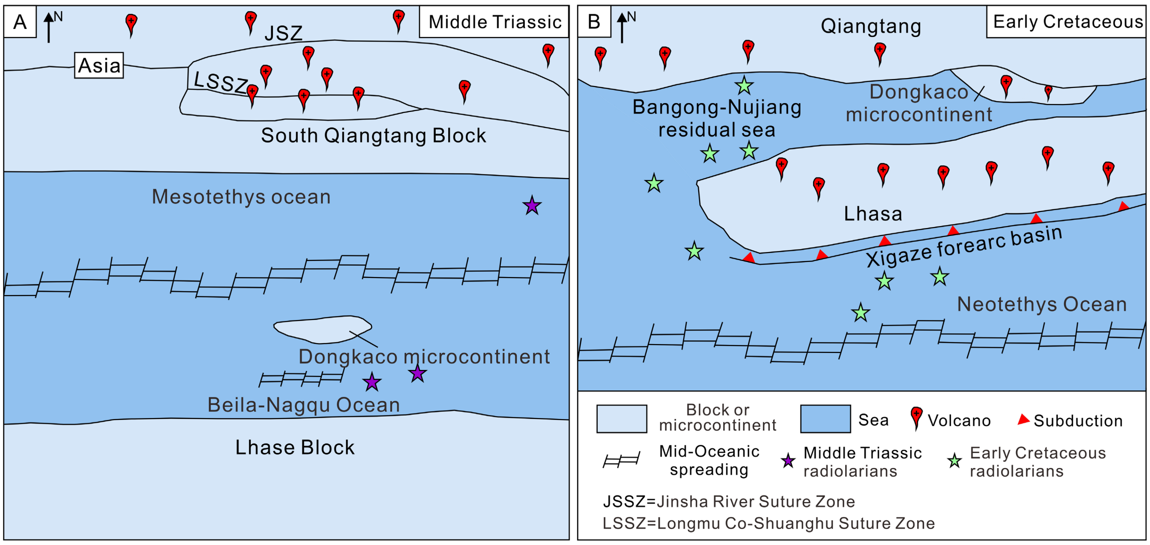

FIGURE 4. Envisaged palaeogeographic evolution of the Bangong-Nujiang oceanic realm and inferred positions of microcontinents (modified from Hu *et al*., 2022).

contrast, recent discoveries of glacio-marine deposits and provenance studies suggest that this microcontinent has a Lhasa Block affinity (Liu *et al*., 2023; Ma *et al*., 2024).

The presence of the BLYMZ in the south of the Dongkaco microcontinent leads to the question with respect to the rifting time of the Dongkaco microcontinent from the Lhasa Block and the opening time of the Beila-Nagqu Ocean as proposed by Hu *et al*. (2022). Recent U-Pb zircon dating on the ophiolites within the BLYMZ shows that the zircon crystallization age of the mafic rocks of the ophiolite is mainly between 148 and 170 Ma (Zhong *et al*., 2017; Tang *et al*., 2018), indicating an opening of the Beila-Nagqu Ocean prior to Middle Jurassic. The radiolarians found in the Nagqu and Beila areas are significant for constraining the opening of the Beila-Nagqu Ocean. The available radiolarian records from the Nagqu area and Beila area confirm that Anisian radiolarians are widespread in the BLYMZ (Wang *et al*., 2021; Ma *et al*., 2024). Especially for the radiolarian *Oertlispongus inaequispinosus* assemblage, this assemblage has been widely reported from the Tethyan and Panthalassa regions (Wang *et al*., 2021). The discovery of the assemblage from the BLYMZ suggests a good connection between the Beila-Nagqu Ocean and other oceans.

The direct sedimentological and petrological evidence for the rifting of the Dongkaco microcontinent is currently lacking. However, the stratigraphic evidence together with radiolarian records are helpful in constraining the opening of the Biela-Nagqu Ocean. For example, according to stratigraphic evidence, from the Carboniferous to the Early Permian, the Dongkaco microcontinent was attached to the Lhasa Block on the northern edge of Gondwana because of the widespread glacial marine sediments as well as similar provenance (Liu *et al*., 2023; Ma *et al*., 2024). Moreover, Late Permian corals and Triassic conodonts found in the limestones in the Jiaqiong area are closely related to the Xiala and Mujiuco formations in the Lhasa Block (Wu *et al*., 2019; Zhang *et al*., 2019). This may suggest that the Dongkaco microcontinent has not been far away from the Lhasa Block before the Late Permian.

Taking all these into consideration, an Early Triassic rifting time for the Dongkaco microcontinent is most plausible. Further study is required in the future.

Closure of the Mesotethys Ocean

There are currently two main views on the closure time of the Mesotethys Ocean. The first view claims that the Mesotethys Ocean closed in the Late Jurassic to Early Cretaceous. The supportive evidence comes from the widespread unconformity between the overlying Shamuluo Formation or Dongqiao Formation and underlying accretionary complex (Mugagangri Group) or ophiolites (*e.g*., Girardeau *et al*., 1984; Ma *et al*., 2017). Importantly, the Shamuluo Formation has a provenance from the South Qiangtang Block and the Mugagangri Group (*e.g*., Huang *et al*., 2017; Li *et al*., 2020). Another opinion, however, suggests that there were oceanic islands or intraoceanic forearc basins in the western segment of the BNSZ in the Early Cretaceous, indicating that its closure time was later than the Early Cretaceous (Fan *et al*., 2014, 2023; Zeng *et al*., 2021).

The fossil record of radiolarians shows that in both the western part of the BNMZ and the SNMZ, there are Early Cretaceous radiolarians in the Rutog (Wang *et al*., 2023), Lagkor Co (Baxter *et al*., 2009), Yunzhug (Qu *et al*., 2003) and Shiquanhe areas (Cui *et al*., unpublished), which indicate that the closure of the western part of the Mesotethys Ocean occurred after the Early Cretaceous (Fig. 4B). It is noteworthy that the Dongkaco microcontinent may have collided with the South Qiangtang Block during the Middle Jurassic (Ma *et al*., 2017; Hu *et al*., 2022). In such case, the main branch of the Meostethys Ocean may have changed to the ocean in the south represented by the SNMZ. Early Cretaceous radiolarians from the Lagkor Co area (Baxter *et al*., 2009) and Late Jurassic to Early Cretaceous ophiolites from the Asa area (Zeng *et al*., 2018) and Yunzhug area (Zhong *et al*., 2015; Zeng *et al*., 2018) together suggest a wide Mesotethys Ocean along the SNMZ.

More importantly, the Early Cretaceous radiolarians in the Rutog area have many similarities to the radiolarians in the Neotethys Ocean. The Early Cretaceous radiolarian fauna from the Rutog area (Wang *et al*., 2023) resembles those produced in the siliceous and clastic rocks of Dazhuqu terrane in YTSZ, sharing *Thanarla brouweri* Tan, *Pseudodictyomitra hornatissima* Squinabol and *Xitus clava* O'Dogherty (Matsuoka *et al*., 2002; Ziabrev *et al*., 2003) (Fig. 3). Those species were also documented from southern India (Bragina & Bragin, 2013), Oman (De Wever *et al*., 1990), Malaysia (Jasin, 1992, 2018) and Iran (Shirdashtzadeh *et al*., 2015; Ozsvárt *et al*., 2020). The correlation between the radiolarian fauna in the different areas mentioned above indicates that at least the western part of the Mesotethys Ocean has good communication with the Neotethys Ocean regarding the radiolarian faunas during the Early Cretaceous.

Conclusion

Although, the insufficient studies on radiolarian faunas in the BNSZ have hampered a full understanding of the evolution of the Mesotethy Ocean. Limited records so far have served as constraints to the opening, evolution and closure of the Mesotethys Ocean. Based on the available radiolarian records in the BNSZ, combined with other disciplines, the following can be concluded: 1) The opening of the Mesotethys Ocean was in the Early Permian, and it has formed a large ocean with abundant radiolarians during the Middle Triassic; 2) The rifting of the Dongkaco microcontinent from the Lhasa Block was most likely in the Early Triassic time; 3) The Mesotethys Ocean closed after the Early Cretaceous. The radiolarians in the western part of the Mesotethys Ocean had good communication with the faunas from the Neotethys Ocean during the Early Cretaceous.

Despite limited radiolarian records in the BNSZ, they are effective in depicting the complex evolution of the Mesotethys Ocean. The radiolarians are highly wanted in the following aspects in the future. Firstly, numerous stratigraphic and palaeobiogeographic studies have proved that the Mesotethys Ocean has opened during the Early Permian time. However, the earliest records of radiolarians in the BNMZ are Middle Triassic. The Permian and Early Triassic radiolarians are anticipated. Secondly, the collision of the Dongkaco microcontinent with the SQB is not constrained by valid radiolarian records in the Dongqiao-Amdo ophiolite, nor the Mugagangri Complex north of the Siling Co, and work in the above areas should be intensified. Finally, there are no radiolarian records to constrain the opening time of the south branch of the Mesotethys Ocean represented by the SNMZ. Future work on radiolarians is anticipated to resolve the above scientific issues.

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