Middle Jurassic–early Cretaceous radiolarian assemblages of the western Yarlung Zangbo Suture Zone: Implications for the evolution of the Neo-Tethys

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Abstract
Cherts in the Zhongba mélangé of the western Yarlung Zangbo Suture Zone (YZSZ) contain well-preserved radiolarian assemblages. These radiolarian assemblages indicate that the Zhongba mélangé has middle Jurassic–early Cretaceous remnant, are coeval with those from the central and eastern parts of the YZSZ. Cherts from the Najiu area yield Aalenian to Aptian radiolarians, while cherts interbedded with siliceous mudstones from the Bielongjiala area yield Aptian radiolarians, indicating that terrigenous-derived sediments were deposited during early Aptian. The above observations indicate that the entire YZSZ have a similar geochronological framework and thus they underwent similar geological evolution: (1) during the Jurassic, the Neo-Tethys was a wide ocean with pelagic sediments distal from continents; (2) during the Cretaceous (around 130–120 Ma), the Neo-Tethys started to subduct along the southern margin of the Lhasa block, and terrigenous-derived siliceous mudstone began deposition.

1. Introduction
The Yarlung Zangbo Suture Zone (YZSZ) in the southern Tibet represents remnants of Neo-Tethyan oceanic lithosphere (Hébert et al., 2012). Existing isotopic geochronological studies on the ophiolites reveal that they were formed around 130–120 Ma (Dai et al., 2013; Wu et al., 2014). These ages are much younger than the timing of the Neo-Tethys opening (as early as late Permian to early Triassic) (Garzanti et al., 1999). This paradox might be explained by facts that these isotopically dated rocks were formed in a supra-subduction zone at the southern margin of the Asia (Dai et al., 2013; Xiong et al., 2016). Therefore, their ages may only represent the initial subduction of the Neo-Tethys rather than the spreading of the ocean.

The radiolarians from the mélangé provide robust constraints on the whole history of the ocean from its initiation at mid-ocean ridge to subduction at a trench because oceanic materials can be accreted into the mélangé by off scrapping of the lower plate (Wakita and Metcalfe, 2005). The radiolarians have been widely used to investigate the occurrence of deep marine sediments and the duration of the Neo-Tethys in the Indus-Yarlung Zangbo Suture Zone (Figs. 1 and 2; Baxter et al., 2011). The radiolarian assemblages indicate that the duration of the deep marine environment range from middle Triassic to early Eocene (Fig. 2; Wu, 1984; Kojima et al., 2001; Matsuoka et al., 2002; Wang et al., 2002; Ding, 2003; Ziabrev et al., 2003, 2004; Aitchison et al., 2007; Li et al., 2007, 2009; Ziabrev et al., 2008; Baxter et al., 2010; Baxter et al., 2011; Liang et al., 2012; Li et al., 2013). Most of the above data are from the central and eastern segments of the YZSZ. However, very little is known about the western segment.

Here we report assemblages of well-preserved and clearly imaged radiolarians from the Zhongba mélangé, the western segment of the YZSZ. These radiolarian assemblages indicate that the deep marine environment occurred in the western part of the YZSZ during middle Jurassic to early Cretaceous.

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Figure 1. Map of the Himalayan region showing the location of Indus, Yarlung–Zangbo and Naga–Andaman sutures zones (after Baxter et al., 2011). The highlighted numbers are thirteen regions where radiolarians have been reported. Location 1, Shergol mélangé (Kojima et al., 2001); Location 2, Spongtang arc (Baxter et al., 2010); Location 3, Nidar ophiolite (Kojima et al., 2001; Zyabrev et al., 2008); Location 4, Zhongba mélangé (Liang et al., 2012; Li et al., 2013; this study); Location 5, Sangdanlin (Ding, 2003; Li et al., 2007); Location 6, Saiqu mélangé (Li et al., 2009); Location 7, Chongdui chert (Wu, 1984); Location 8, Xialu chert (Matsuoka et al., 2002); Location 9, Dazhuqu terrane (Zyabrev et al., 2003); Location 10, Bainang terrane (Zyabrev et al., 2004); Location 11, Zongzhuo Formation (Li et al., 2009); Location 12, Zedong mélangé (Wang et al., 2002; Aitchison et al., 2007); Location 13, Naga ophiolite (Baxter et al., 2011). YZSZ, Yarlung Zangbo Suture Zone; BNSZ, Bangong Nujiang Suture Zone; JSSZ, Jinshajiang Suture Zone.
Shergol ophiolite (Kojima et al., 2001)  
Spongtag arc (Baxter et al., 2010)  
Nidar ophiolite (Kojima et al., 2001; Zyabrev et al., 2008)  
Zhongba mélange (Li et al., 2012)  
Zhongba mélange (this study)  
Zhongba mélange (Li et al., 2013)  
Zheba Group (Ding et al., 2003)  
Sangdanlin mélange (Li et al., 2007)  
Saiqu mélange (Li et al., 2009)  
Chongdui chert (Wu., 1984)  
Xialu chert (Matsuoka et al., 2002)  
Dazhuqu terrane (Ziabrev et al., 2003)  
Bainang chert (Ziabrev et al., 2004)  
Zongzhuo Formation (Li et al., 2009)  
Zedong mélange (Aitchison et al., 2007)  
Jinlu chert (Wang et al., 2002)  
Naga ophiolite (Baxter et al., 2011)

Figure 2. Chronostratigraphic chart summarising the age constraints of deep-water sedimentation in the Neo-Tethyan Ocean (see Fig. 1 caption for references).
2. Geologic setting

The Tibetan Plateau is an amalgamation of several blocks separated by major suture zones including An'emaqin-Kunlun, Jinshajiang, Bangong-Nujiang, and YZSZ (Yin and Harrison, 2000). The southernmost YZSZ is the youngest suture zone and has been widely considered to mark the collision zone between India and Eurasia following the latest early Cretaceous–early Paleogene closure of the Neo-Tethys (Allegre et al., 1984; Hébert et al., 2012; Dai et al., 2013).

The YZSZ roughly parallels the Yarlung Zangbo River forming a narrow E–W-trending belt. Towards the west, it connects with the NW-trending Indus suture, while towards the east it crosses the Yarlung Zangbo River in Medog County and extends further southward into Burma and Thailand (Yin and Harrison, 2000). Four basic tectonic units are related to the YZSZ: (1) the Gangdese arc, (2) the Xigaze forearc basin, (3) the Yarlung Zangbo ophiolite, and (4) the accretionary prism (Wang et al., 2012; Dai et al., 2013).

The Zhongba ophiolitic mélangé is located in the western part of the YZSZ. It consists of various chaotic blocks of mantle peridotite (Dai et al., 2011b), late Devonian gabbro (Dai et al., 2011a), early Cretaceous diabase (Dai et al., 2012), purplish red and greenish gray bedded chert, massive and pillow basalt, limestone, and bedded siliceous mudstone with a heterogeneous and variously deformed matrix (Raymond, 1975; Festa et al., 2012).

Here we report new radiolarians from four localities (Fig. 3). They are Py (29°56.80′N, 83°18.58′E) and Pyz (29°58.58′N, 83°18.87′E) located in the Najiu area, YDA (29°47.34′N, 83°44.74′E) and YDB (29°47.33′N, 83°43.32′E) located in the Bielongjiala area.

In the locations of YDA and YDB, the siliceous mudstone and shale are interbedded with the chert.

3. Materials and methods

Forty-six potentially radiolarian-bearing samples were collected from purplish red or greenish gray chert and siliceous mudstone in these four locations. The samples were processed in biostratigraphy laboratory of Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences. Each sample was broken into 2–3 cm³ pieces, suspended in a plastic beaker and immersed in 4–5% hydrofluoric acid for 24 h. Acid residues were sieved, with microfossils concentrated in 380–380 μm. Samples were then dried and the residues were collected. The process from immersing to collecting was repeated 10 times for each sample to obtain enough specimens.

Radiolarians were picked by stereoscopic microscope and mounted onto aluminium stubs, coated with Ti-Au alloy-coated then photographed using a scanning electron microscope (SEM). More than 800 SEM photomicrographs were taken in Australian Centre for Microscopy & Microanalysis (ACMM) in the University of Sydney.

4. Age assignment

Highly diverse and well-preserved radiolarians were collected from purplish red chert and siliceous mudstone (Figs. 4 and 5). Identification of taxa and age assignment for middle Jurassic to early Cretaceous radiolarian assemblages were based on detailed radiolarian taxonomic and biostratigraphic studies in the Tethys (Jud, 1994; O’Dogherty, 1994; Baumgartner et al., 1995; De Wever et al., 2001; O’Dogherty et al., 2009). The zonal scheme
Figure 4. Composite plate of representative radiolarians from the Zhongba sample locations (all scale bars represent 100 μm). Sample Py-0-f9: (1) Archaeodictya gifuensis Takemura; (2) Homoeoparonaella sp. aff. H. elegans (Pessagno); (3) Lactorum (?) sp.; (4) Parahsuum (?) magnum Takemura; (5) Stichocapsa convexa Yao; Sample Py-0-f14: (6) Parahsuum (?) grande Hori & Yao; Sample Py-0-f15: (7) Parvicingula dhimenaensis sp. A; (8) Stichocapsa robusta Matsuoka; (9) Parahsuum maxwelli gr. (Pessagno); (10) Tricolocapsa tetragona Matsuoka; Sample Py-0-f12: (11) Hiscocapsa (?) sp.; (12) Napora deweveri Baumgartner; (13) Parvicingula dhimenaensis Baumgartner; (14) Podobursa (?) aff. P. quadriculate (Steiger); (15) Protunuma japonicus Matsuoka & Yao; (16) Zhamoidellum ovum Dumitrice; Sample Pyz-1-f3: (17) Angulobracchia (?) portmanni portmanni Baumgartner; (18) Loopus nuda (Schaaf); (19) Sethocapsa (?) zweilii Jud; (20) Tethysetta boessi gr. (Parona); (21) Xitus sp.; Sample Pyz-5-f5: (22) Podobursa typica (Rüst); (23) Squinabollum asseni (Tan); (24) Zhamoidellum (?) sp.
Figure 5. Composite plate of representative radiolarians from the Zhongba sample locations (all scale bars represent 100 μm). Sample YDA03: (1) Cryptamphorella gilkeyi (Dumitrica); (2) Cryptamphorella sp.; (3) Holocryptocanium barbui Dumitrica; (4) Pseudodictyomitria sp. cf. P. lodogaensis Pessagno; (5) Rhopalosyringium fossile (Squinabol); (6) Stichomitra japonica (Nakaseko & Nishimura); (7) Tethysseta boesii gr. (Parona); (8) Thanarla brouweri (Tan); (9) Xitus sp. aff. X. spicularius (Aliev); (10) Xitus clava (Parona); Sample YDA05: (11) Acaeniotyle diaphorogona gr. Foreman sense Baumgartner; (12) Podobusa typica (Rüst); (13) Xitus clava (Parona); Sample YDA13: (14) Pseudodictyomitria lanceolat Schaa; (15) Pseudodictyomitria lodogaensis Pessagno; (16) Thanarla lacrimula (Foreman); (17) Xitus elegans (Squinabol); Sample YDB10: (18) Crolanium puga (Schaaf); (19) Holocryptocanium barbui Dumitrica; (20) Stichomitra mediocris (Tan); (21) Thanarla brouweri (Tan); (22) Thanarla lacrimula (Foreman); (23) Thanarla sp.; (24) Xitus clava (Parona); (25) Xitus spicularius (Aliev).
established in Japan and the western Pacific (Matsuoka, 1995a,b) was also referenced. The stratigraphic positions of the fossiliferous sediments were assigned with Unitary Association (UA) zones correlated to the geological time scale of Gradstein et al. (2012). Forty-six species belonging to 28 genera were identified (Fig. 6).

Sample Py-0-f9 contains abundant and moderately preserved radiolarian shells assigned to five species within four genera (Fig. 6). Among them, *Homoeoparonaecia* sp. aff. *H. elegans* (Pessagno) appears in UAZones 1–3, *Stichocapsa convexa* Yao appears in UAZones 1–11, *Parahsuum* (?) *magnum* Takemura appears in UAZones 2–5 (Fig. 4; Baumgartner et al., 1995). The overlapping age range of these species suggests a late Aalenian to early Bajocian (UAZones 2–3) age range.

Sample Py-0-f14 yields rare radiolarian shells assigned to 5 species (Fig. 6). Among these Jurassic radiolarians, *Parahsuum* (?) *grandae* Hori & Yao and *Parahsuum* (?) *natoence* (El Kadiri) appear in UAZones 1–3. *S. convexa* Yao appears in UAZones 1–11, *Transhsuum maxwelli* gr. (Pessagno) appears in UAZones 3–10 (Baumgartner et al., 1995). Co-occurrence of them suggests an early Bajocian (UAZones 3) age.

Sample Py-0-f15 contains *Parvicingula dhimenaensis* sp. A, *T. maxwelli* gr. (Pessagno), *Trilococapsa tetragona* Matsuoka, and *Stichocapsa robusta* Matsuoka (Fig. 4). *T. tetragona* Matsuoka existed in a relatively short age range which constrains the sample’s age ranging from late Bajocian to early Bathonian (UAZones 5).

Sample Py-0-f12 yields abundant and well-preserved radiolarian shells referred to eight species (Fig. 6). Among them, *Napora deweveri* Baumgartner appears in UAZones 7–11, *P. dhimenaensis* Baumgartner appears in UAZones 3–11, *Podobursa* (?) *sp.* aff. *P. quadraculatea* (Steiger) appears in UAZones 9–17, *Protunuma japonicus* Matsuoka & Yao appears in UAZones 7–12, *Zhamoidella ovum* Dumitra appears in UAZones 9–11 (Fig. 4; Baumgartner et al., 1995). The overlapping age range of this species indicates a late Oxfordian to early Tithonian (UAZones 9–11) age range.

Sample Pyz-1-f3 contains abundant and moderately preserved radiolarian shells including *Angulobracchia* (?) *portmanni* portmanni Baumgartner, *Loopus nuda* (Schaaf), *Tethysetta boesii* gr. (Parona), *Sethocapsa* (?) *zevelli* Jud, and *Xitus* sp (Fig. 4). These species appear in UAZones 13–22, UAZones 12–16, UAZones 9–22, UAZones 14–19 respectively (Baumgartner et al., 1995; Matsuoka et al.,...
The overlapping age range of these species indicates a Berriasian to early Valanginian (UAZones 14–16) age range.

Abundant and moderately preserved radiolarians from sample Pyz-5-f5 are assigned to six species within five genera (Fig. 6). Based on Unitary Associations of mid-Cretaceous, Podobursa typica (Rüst) appears in U.As. 1–4, Rhopalosyringium fossile (Squinabol) appears in U.As. 4–12, Squinabollum asseni (Tan) appears in U.As. 1–10, Thanarla brouweri (Tan) appears in U.As. 1–11 (O’Dogherty, 1994). The overlapping age range of these species suggests an early Aptian (Turbocapsula Zone, Verbeekii Subzone) age.

Abundant, well-preserved and diversified radiolarians extracted from sample YDAO3 are identified as 11 species within nine genera (Fig. 6). According to Unitary Associations of mid-Cretaceous (O’Dogherty, 1994), the co-occurrence of T. boessi gr. (Parona) and R. fossile (Squinabol) indicates an early Aptian (Turbocapsula Zone, Verbeekii Subzone) age.

Sample YDAO5 yields moderately preserved radiolarian shells assigned to seven species within seven genera (Fig. 6). Among them, P. typica (Rüst) appears in U.As. 1–4, while Pseudodictyomitra lodo-gaensis Pessagno appears in U.As. 4–9. The co-occurrence of these two species suggests an early Aptian (Turbocapsula Zone, Verbeekii Subzone) age.

Sample YDA13 contains abundant and moderately preserved radiolarian shells assigned to nine species within six genera (Fig. 6). P. typica (Rüst) appears in U.As. 1–4, while P. lodo-gaensis Pessagno appears in U.As. 4–9 (O’Dogherty, 1994). The co-occurrence of these two species suggests a mid Aptian (Turbocapsula Zone, Costata Subzone) age.

Moderately to well-preserved radiolarian shells obtained from sample YDB10 are assigned to eight species within five genera (Fig. 6). Thanarla lacrimula (Foreman) appears in U.As. 1–6, while Xitus spicularius (Aliev) appears in U.As. 6–19 (O’Dogherty, 1994). The co-occurrence of these two species suggests a mid Aptian (Turbocapsula Zone, Costata Subzone) age.

5. Discussion

5.1. Age constraints for the Indus-Yarlung Zangbo Suture Zone

Liang et al. (2012) has reported late Paleocene radiolarians fauna from Jiaza Village in the Zhongba mélange, while within the same mélange, Li et al. (2013) presented a late Jurassic radiolarian assemblage which is the oldest radiolarian age in this region (Fig. 2). Our studies reveal that the pelagic deposits of the chert sequence existed from at least the early middle Jurassic (Aalenian) to late early Cretaceous (Aptian) (Fig. 2).

Generally, the above radiolarian assemblages in the Zhongba mélange are chronologically consistent with those from the Spongtang massif in NW India (Baxter et al., 2010), Dazhuxu ophiolite (Ziabrev et al., 2003), Bainang terrane (Ziabrev et al., 2004), and Xialu chert (Matsuoka et al., 2002) near Xigaze in the middle segment of the YSZZ, and Naga ophiolite in NE India (Figs. 1 and 2; Baxter et al., 2011). The above observations indicate that the Neo-Tethys occurred widely during the middle Jurassic to early Cretaceous.

5.2. Implications for the evolution of the Neo-Tethys

The radiolarian assemblages from the red cherts in the Bainang area reveal the oldest ages of late Triassic (Ziabrev et al., 2004), indicating that the occurrence of Neo-Tethys during that time, consistent with the studies of rifting-related mafic rocks (Garzanti et al., 1999) and the Tethyan Himalayan passive margin (Jadoul et al., 1998).

Ages of the radiolarian assemblages are focused on the middle Jurassic–early Cretaceous (Fig. 2), indicating this is critically important stage of the Neo-Tethys evolution. In the Beiligjiala area, the Aptian cherts are interbedded with siliceous mudstone and shale. Therefore, the ages of these terrigenous-derived sediments were also deposited during the Aptian. In Xialu of the central segment of the YSZZ, Matsuoka et al. (2002) also reported the lithofacies transition from chert to siliceous mudstone occurred around the Barremian/Aptian boundary. The occurrence of terrigenous-derived sediments during Aptian implies that a new stage of subduction of the Neo-Tethys occurred. This conclusion is consistent with studies from the Yarlung Zangbo ophiolites which also reveal one stage of subduction initiation of the Neo-Tethys occurred around 130–120 Ma (Dai et al., 2013).

The above observations indicate that the entire YSZZ have a similar geochronological framework and thus underwent similar geological evolution: (1) during the Jurassic, the Neo-Tethys was a wide ocean with pelagic sediments far away from continents; (2) during the Cretaceous (around 130–120 Ma), the Neo-Tethys started to subduct along the southern margin of the Lhasa block.

The youngest age of the radiolarians is Paleocene–Eocene (Ding, 2001; Li et al., 2009; Liang et al., 2012). This indicates that the youngest deep marine sediments were preserved in the YSZZ. Evidence from foraminifers and calcareous nanofossils in the Tethyan Himalaya reveals that the shallow marine conditions occurred widely during Eocene (Jiang et al., 2016). Considering the oldest (Wang et al., 2002) and the youngest deep marine sediments, the duration of the Neo-Tethys was at least more than 180 m.y.

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