Early Eocene Radiolarian Fauna from the Sangdanlin, Southern Tibet: Constraints on the Timing of Initial India-Asia Collision

WANG Tianyang[1, 2], LI Guobiao[1, 2, *], LI Xinfa[1, 2] and NIU Xiaolu[1, 2]

1 *State Key Laboratory of Environmental Geology and Biogeology, China University of Geosciences, Beijing 100083, China*

2 *School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China*

Abstract: This is a new report on the early Eocene radiolarian fauna from the Sangdanlin section in the Gyirong region, along the southern margin of the Yarlung Zangbo Suture Zone. The Sangdanlin section measured in this study is divided into three lithostratigraphic units from bottom to top: the Zongzhuo, Sangdanlin, and Zheya formations. Abundant radiolarian fossils were obtained from the Sangdanlin section and 54 species of 30 genera were identified and assigned as follows: *Cryptamphorella conara-C. macropora* the late Cretaceous Zone and *Amphisphaera coronate, Buryella tetradica-Bekoma campechensis,* and *B.bidartensis-B. divaricata* the Paleocene-early Eocene Interval Zones. The Paleocene–early Eocene radiolarian zones are comparable to the radiolarian zones RP4-RP8 in New Zealand. Based on the data of radiolaria and lithofacies, it is suggested that the Zongzhuo Formation should be deposited along the base of the north-facing, continental slope of the Greater Indian continental margin, and the Sangdanlin Formation should be a deep marine, sedimentary sequence located in a foreland basin. The early Eocene radiolarian fauna in the Sangdanlin Formation constrains the initial age of the India-Asia collision to no later than 53.6 Ma.

Key words: Radiolarian, Eocene, India-Asia collision, Neo-Tethys, southern Tibet

1 Introduction

The Tethys Ocean is subdivided into a northern ocean called the Paleo-Tethys and a southern one called the Neo-Tethys (Newman, 1994). The evolution of the Neo-Tethys has always been an intriguin subject in the study of geology. The initiation and development of the Qinghai-Tibetan Plateau is closely related to the termination of the Neo-Tethys and to the collision between India and Asia (Wu Zhenhan et al., 2016). The collision is still a rather vague term, and the collision between India and Asia is often equated with the final closure of the Neo-Tethys Ocean (Patriat and Achache, 1984; Blondeau et al., 1986; Searle et al., 1986). Therefore, the end of marine sedimentation is commonly used as a symbol of the initial plate collision (Rowley, 1996, 1998). The time of the cessation of marine deposits in the Neo-Tethys is a long-debated topic. In the literature, estimations of the time of the India-Asia collision, range from as old as the Late Cretaceous to as recent as the Miocene (Blondeau et al., 1986; Garzanti et al., 1987; Yin and Harrison, 2000; Aitchison et al., 2007; Najman et al., 2010; Cai et al., 2011; Hu et al., 2012; Zhang et al., 2016). Rowley (1996) reviewed the stratigraphic data for the time of initial collision between India and Asia and suggested that the only well-constrained data must be from the Zanskar-Hazara region, which indicated an age dating to the late Ypresian (~52Ma).

Researchers have used a variety of evidence to constrain the age of collision, with increasing precision and accuracy, by the study of sedimentology, structural geology, stratigraphy, magmatism, paleomagnetism, and metamorphism (Ding et al., 2005; Zhu et al., 2005; Li Yalin et al., 2007; Liang yinping et al., 2012; Xu Zhiqin et al., 2016; Hu et al., 2015; Liu Jianguo et al., 2017). Wan Xiaoqiao and Ding Lin (2002) found abundant planktonic foraminiferal fauna on the top of the Zongzhuo Formation in the northern part of the Gyirong region, which was designated as being from the late Masstrichtian and was correlated to the upper *Gansserina gansseri* Zone and lower *Abathomphalus mayaroensis* Zone. The studies and

* Corresponding author. E-mail: liguobiao@cugb.edu.cn

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contract of stratigraphy and paleontology in the Gyirong-Gyangze region indicated that the Tethys Himalayan regression should progress from east to west (Wan Xiaoqiao and Ding Lin, 2002; Li Guobiao et al., 2005).

In this paper, we provide lithology and biostratigraphy evidences from the Sangdanlin section in the Gyirong region along the southern margin of the Yarlung Zangbo Suture Zone which constitutes the northernmost and probably earliest preserved record of the initial India-Asia collision (Ding et al., 2005; Hu et al., 2012; Wu et al., 2014; DeCelles et al., 2014). Abundant radiolarian fossils were obtained from the Sangdanlin section and four radiolarian zones were distinguished. These zones have been interpreted as ages from the late Cretaceous to the early Eocene and are a valuable tool for reconstructing the processes of the India-Asia collision.

2 Geological Setting

The Sangdanlin section (Fig. 1 and Fig. 2a) is located in ~46km north of the town of Gyirong, southern Tibet. This section was defined as deposited on the Greater Indian passive continental margin, and was mainly composed of radiolaria-bearing chert and flysches (Jadoul, 1998; Ding Lin, 2003), which represented the northern Tethyan passive margin succession and was accumulated in the central trench of the foreland region (Ding et al., 2005). Li Yalin et al. (2007) and Wang et al. (2011) considered the Sangdanlin section as consisting of an exposed tectonic block of sedimentary strata embedded in a mud matrix tectonic mélange zone. The Sangdanlin deposited in a foreland basin, which the provenance being the Gangdese arc and the Yarlung Zangbo suture zone. Hu et al. (2016) confirmed that the "Sangdanlin section displayed a continuous, north-dipping succession with well-preserved stratigraphic relationships from base to top. Even though it might be locally affected by a few faults, in no way it could be interpreted as a mélange." In this paper, we follow the explanation that the Sangdanlin section was a continuous, north-dipping normal sedimentary.

The Himalayan orogenic belt is composed of a series of east-west trending litho-tectonic units. From north to south, these units included: the Gangdese magmatic arc, the Xigaze forearc basin, the Yarlung Zangbo suture zone and the Tethyan Himalayan sedimentary sequence, all of which are separated by major fault systems (Fig. 1). The YZSZ marks the contact between India and Asia, and includes ophiolites and tectonic mélange with serpentinite or shale matrix (Cai et al., 2012; Chan et al., 2015; Xu et al., 2015). The YZSZ is a generally narrow (<15 km), approximately east-west belt of oceanic rocks which represents the remnant of the Neo-Tethys Ocean. The Tethyan Himalayan sedimentary sequence is generally separated by the Gyirong-Kangmar thrust into northern and southern zones(Li et al., 2011). The upper Cretaceous-Paleocene of the northern subzone sequence is mainly

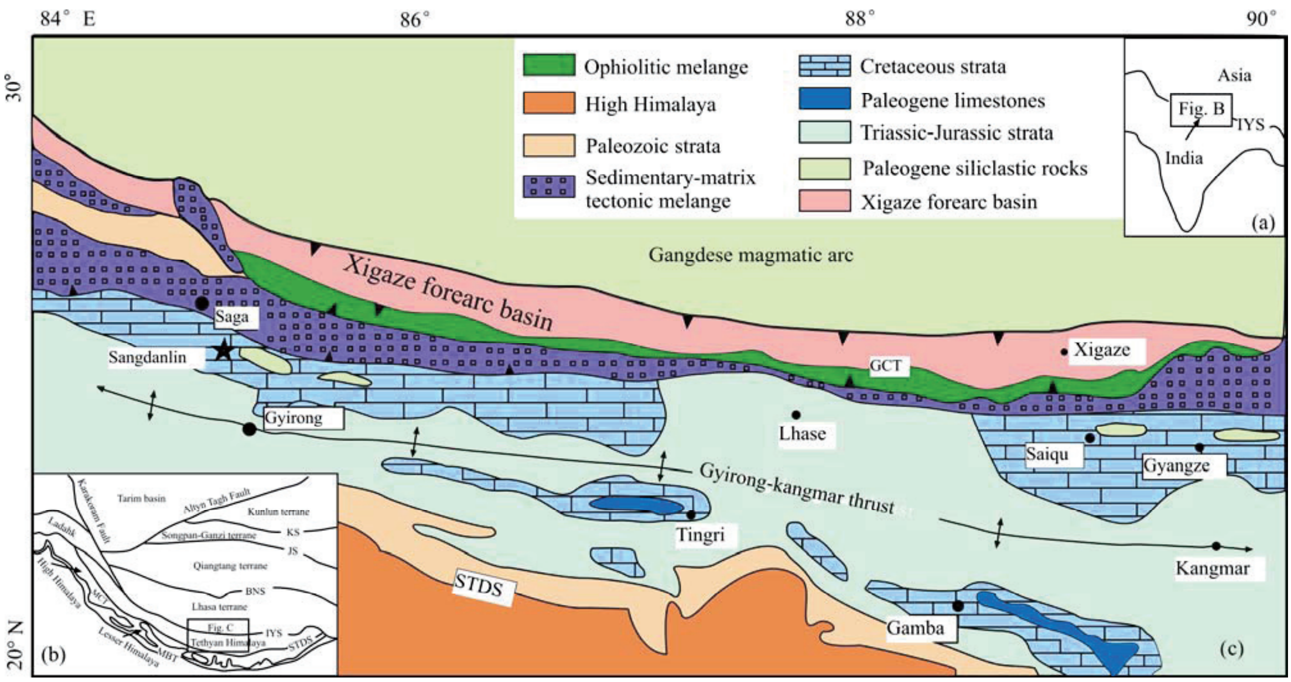

Fig. 1. Simplified tectonic map of the southern central Tibet and location of the study aera.
(a), Inset map shows location of study area between Aisa and India; (b), Inset map with major tectonic units and boundaries in Tibet; (c), Schematic geological map of the Tethyan Himalaya of Tibet showing the study areas of Sangdanlin aera, modified from Li et al. (2005). IYS, Indus–Yalung Zangbo Suture; STDS, South Tibet Detachment System; MBT, main boundary thrust; MCT, main central thrust; BNS, Bangong Nujiang Suture; JS, Jinsha Suture; KS, Kunlun Suture; GCT, Great Counter Thrust.

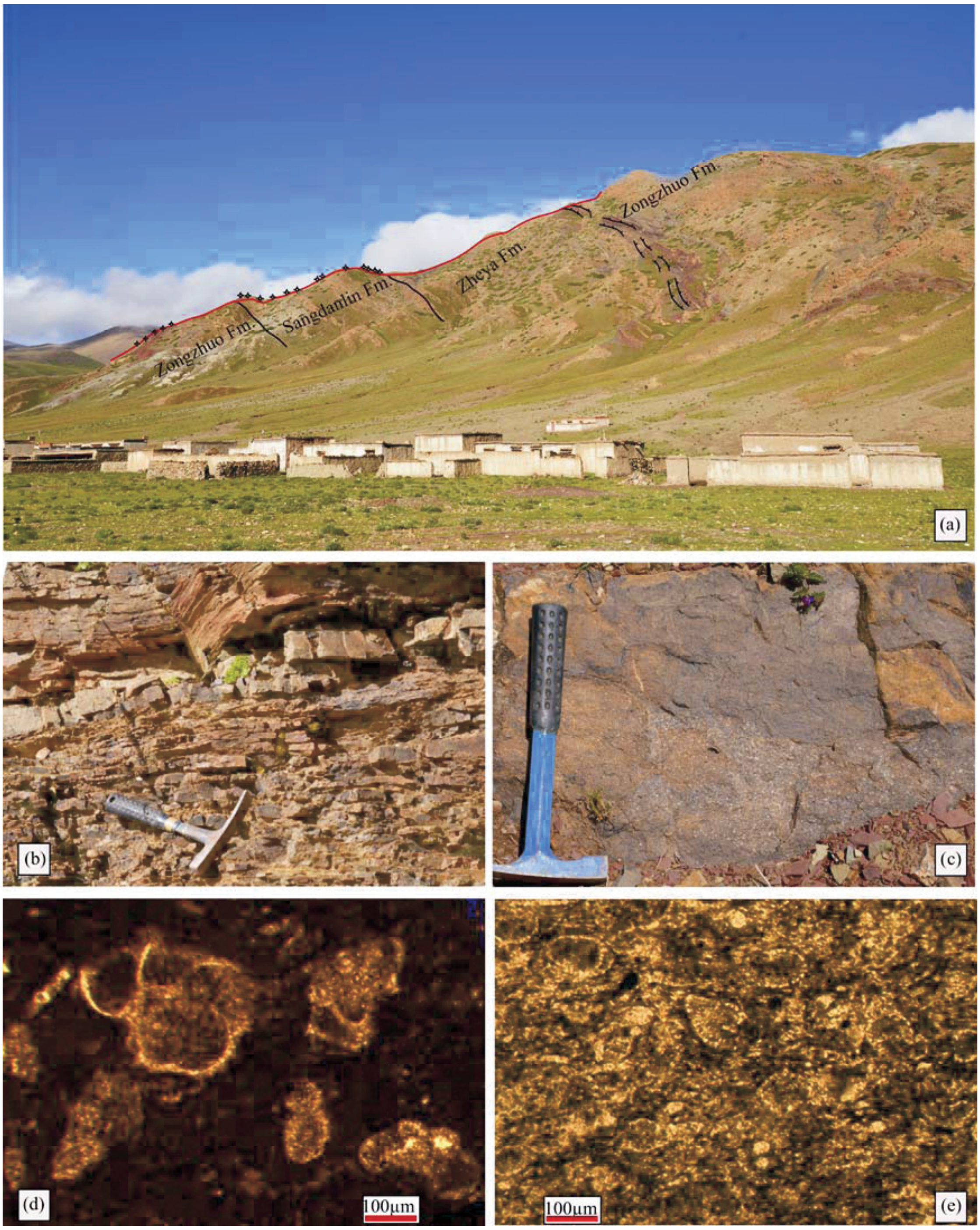

Fig. 2. Photographs of Sangdanlin section lithofacies.
(a), Panoramic photograph of the Sangdanlin section, look northwestward; (b), Detail of the turbiditic sandstones of the Zongzhuo Formation; (c), Graded bed with fine gravel at the base; (d), The planktonic foraminiferal in the limestone; (e), Microfacies characteristics of the radiolarian chert in the Sangdanlin Formation (SD181).

composed of upper Cretaceous-Paleocene quartz sandstone, siltstone, and shale (sourced from the Indian continent), and the intercalated layers of radiolarian chert, planktonic foraminifera-bearing limestone, which indicates a deep-water environment (Wan Xiaoqiao and Ding Lin, 2002; Ding et al., 2005). And the lower-middle Eocene sediments show a coarsening -upward trend from shale to pebbly sandstone, whereby the Asian-derived detritus is proposed to indicate the onset of the India-Asia collision (Ding et al., 2005; Wang et al., 2011; DeCelles et al., 2014). The southern unit is dominated by the Paleocene – Eocene shallow-water shelf carbonate and clastic sediments rocks (Jadoul et al., 1998; Hu et al., 2010).

3 Sedimentology

There are different views on the age, stratigraphy and tectonic attributes of the sedimentation of the Sangdanlin section. The radiolarians from this section were previously interpreted as Triassic (Sheng Jinzhang, 1976) or Late-Paleocene to Early-Oligocene (Li Hongsheng, 1985). According to the characteristics of planktonic foraminiferal assemblages, the Sangdanlin section was consisted of the upper Zongzhuo Formation of the Maastrichtian in age (Wan Xiaoqiao and Ding, 2002).

The stratigraphic units exposed in the Sangdanlin area were discussed by Ding Lin (2003), Ding et al. (2005), Wang Jiangang et al. (2008), Wang et al. (2011), DeCelles et al. (2014) and Hu et al. (2015, 2016). By Ding Lin (2003), this set of deposits in Sangdanlin section was named after Zheba Group, which was well exposed on the southern side of the Yalung-Zangbo suture zone and represented the foreland basin sediments generated by the Asian continent loading the northern margin of Indian continent. The Zheba Group is composed of the lower Sangdanlin Formation dominated by cherts and siliceous shales and the upper Zheya Formation reflected the feature of the flysch. The radiolarian faunas from the Zheba Group were assigned to Paleocene RP1-RP6 zones (Ding Lin, 2003). Li Yalin et al. (2007) considered that the chert and clastic rocks in study areas usually were divided by faults and disordered in sequence. The top and bottom boundaries of the section could not be identified in the field and the thickness of sediments distinguished from wedge-shaped structure in a foreland basin. This paper adopts Ding Lin's (2003) lithostratigraphic subdivision scheme on the Sangdanlin section which was divided into Zongzhuo, Sangdanlin and Zheya formations from bottom to top (Fig. 3).

3.1 Zongzhuo Formation

The Zongzhuo Formation is composed of 113m-thick shale, siliceous shale, chert, lithic sandstone and quartzose sandstone. The 45m-thick lower part of the Zongzhuo Formation is composed of grayish green calcareous, carbonaceous shale bedded with gray laminated coarse-grained quartzose sandstone. And the upper part consists of about 68m-thick burgundy chert, gray quartzose sandstone, bedded with gray-greenish shale and yellow, greenish clay shale. The graded bedding was found in the top of sandstone bed, the gravel layer was 10 cm thick, and gravels had uniformity size, good sorting and roundness (Fig.2c). Owing to rapid deposition, the stratification was rare in such deposits, which was interpreted as high-density turbidity. Wang et al. (2011), DeCellse et al. (2014) and Hu et al. (2015) also interpreted the sandstone interval in the Zongzhuo Formation as turidites. The uppermost part of the interval was consisted of finer-grained deposits with clay and burgundy shale.

Radiolarian fossils including *Archaeodictyomitra lamellicostata*, *Cryptamphorella macropora*, *C. conara*, *Dictyomitra* sp., *Stichomitra stoki*, *Patellula euessceei* and *Pseudoaulophacus riedeli* et al. were identified from the burgundy siliceous shale of the Zongzhuo Formation, which indicated a Late Campanian age.

3.2 Sangdanlin Formation

The Sangdanlin Formation overlying the Zongzhuo Formation was a total of 143m thick deposition. It is mainly composed of variegated (burgundy, green and gray) siliceous shale, radiolarian chert, and lithic quartzose sandstone (Ding et al., 2005; DeCelles et al., 2014). The bottom of the Sangdanlin Formation was a set of gray lithic quartzose sandstone of 5 meter thickness. Upward the Sangdanlin formation dominated by burgundy and gray-greenish siliceous shale and radiolarian chert bedded with large-scale tectonic fold and disrupted shale layers. Abundant and moderately to well-preserved radiolarians were embedded and three radiolarians zones were identified in the Sangdanlin Formation included *Amphisphaera coronate*, *Buryella tetradica-Bekoma campechensis* and *Bekoma campechensis-B. divaricata* zones, which were assigned to Paleocene to early Eocene in age. Further up the siliceous shale/chert-dominated continued for nearly 120m and then sandstones gradually increase. The most important development in the Sangdanlin Formation included horizontally and rippled laminated medium-grained sandstone, horizontally laminated massive coarse-grained lithic sandstone, and variegated (green, burgundy and gray) laminated siliceous shale. The siliceous shale and radiolarian chert in the Sangdanlin Formation were interpreted as the results of pelagic biogenic silica deposition (Ding et al., 2005; Wang et al., 2011; DeCelles et al., 2014).

3.3 Zheya Formation

The Zheya Formation comformably overlying the Sangdanlin Formation is composed of at least 200 m-thick flysches, which consists of dark gray siliceous shale interbedded with lithic sandstone and fine-grained siliceous rock. The bottom of the Zheya Formation consists of dark, gray carbonaceous shales intercalated with medium-to coarse-grained lithic sandstone. Normal grading, flute casts, and slump structures were present in the sandstone beds. The index radiolarian species were not present.

In the Sangdanlin section, the top of the Zheya Formation is overlied by the Zongzhuo Formation with a

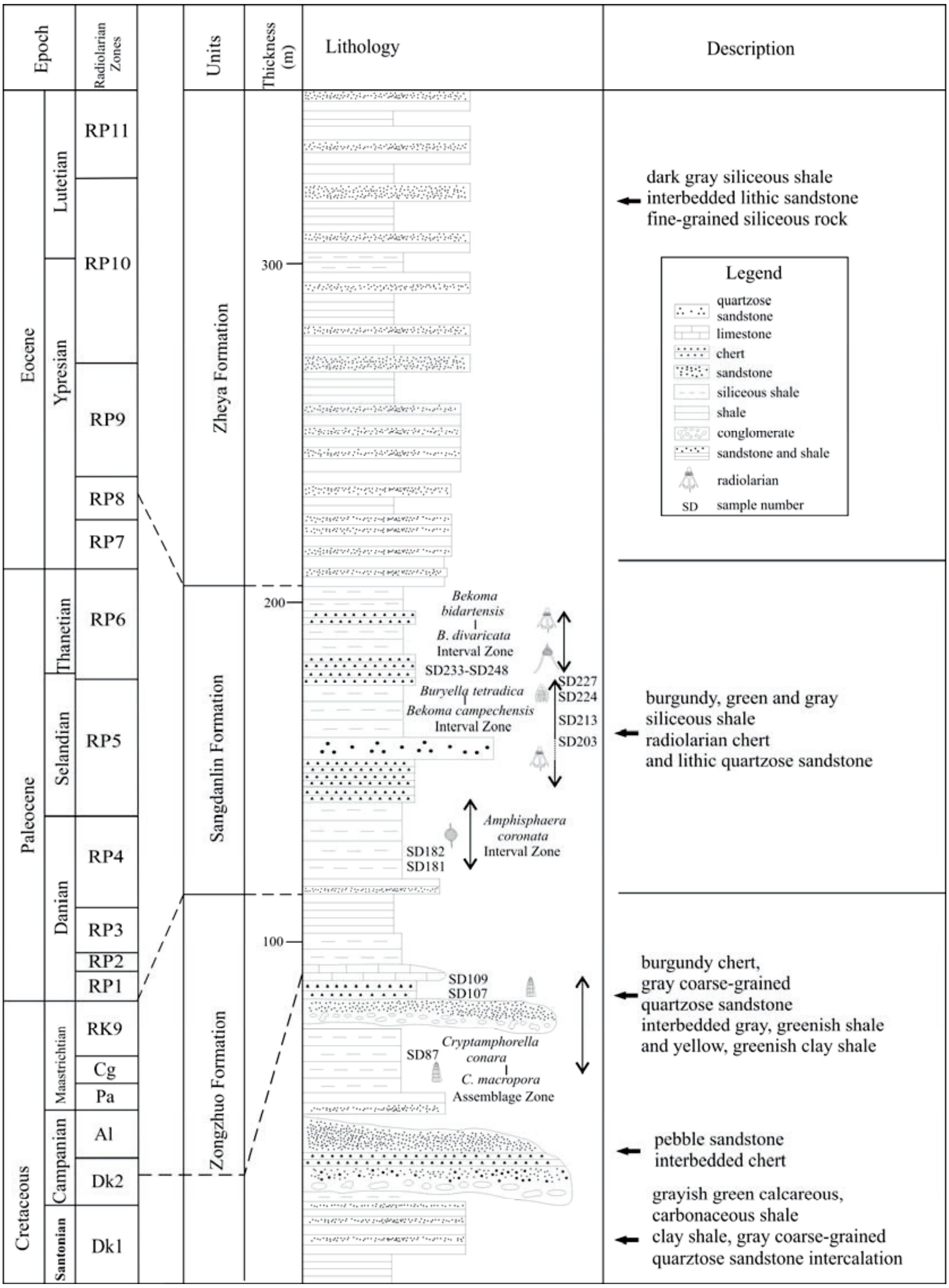

Fig. 3. Lithostratigraphic column for Upper Cretaceous - lower Eocene sequences in the Sangdanlin aera.
Samples were processed by standard methods for radiolarian extraction which are shown in this fig.

thrust fault between them. Abundant limestone concretions with late Cretaceous planktonic fossilis (Fig. 2d) were found in the sandstone and siliceous shale of the Zongzhuo Formation, the lithologic and paleontological characteristics of which was similar to that of the Zongzhuo Formation in Gyangze area.

Overall, the variety of lithofacies in the Zheya Formation was much more complicated than Zongzhuo and Sangdanlin formations, and however, the assemblage of the physical processes responsible for deposition was similar. Most of the sandstone may be interpreted as density current deposit (Lowe, 1982; Mutti, 1992; DeCelles et al., 2014).

4 Material and Methods

The chert samples were processed by standard methods for radiolarian extraction (Pessagno and Newport, 1972). Siliceous rocks and other siliceous lithologies with some carbonate component were treated as follows: samples were first broken into pieces of a few cubic centimeters, washed with distilled water and then dissolved in plastic mesh bags containing diluted (4%–5%) hydrofluoric acid for 24h. After the reaction ceased, the samples were sieved with 48μm and 380μm screen. Samples larger than 380μm were soaked again in renewed 4%–5% HF for 24 h. Then, the resulting residue was boiled with 5% H_2O_2 and sieved again and left to dry. Radiolarians were picked from the dried residue by using a very thin needle under transmitted light, pasted on the stubs, gold-coated and photographed by using a Scanning Electron Microscope (SEM).

5 Radiolarian Bistratigraphy

In deep-water sedimentary regions with high tectonic intensity, other diagnostic fossils are usually absenting. Radiolarian assemblages could play an important role in the biostratigraphy. The radiolarian preservation and abundance were largely controlled by the process of dissolution in these regions. In this work, 423 samples were collected for radiolarian abstraction from the green, burgundy and gray laminated siliceous shale and siliceous rocks in Zongzhuo and Sangdanlin formations of which 43 samples yielded well-preserved radiolarians. 54 species of 30 radiolarian genera (Figs. 4 and 5) were identified and 4 radiolarian zones were recognized, which provides this set of strata with an age of Late Cretaceous to early Eocene (Fig. 6). Planktonic foraminiferas were found in upper Zongzhuo Formation (Fig. 2d).

The Late Cretaceous radiolarian assemblage of the investigated section was compared with the radiolarian zonations presented by Forman (1975, 1977), Pessagno (1976), Sanfilippo and Riedel (1985), O'Dogherty (1994), Vishnevskaya and DeWever (1998), Hollis and Kimura (2001). The Paleocene samples were main dated on the basis of Riedel and Sanfilippo (1970, 1971, 1978), Foreman (1973a, 1973b), Sanfilippo and Riedel (1973), Nishimura (1987, 1992), Sanfilippo and Nigrini (1998a, 1998b), Sanfilippo and Hull (1999); De Wever et al., (2001), Liu and Aitchison (2002), Hollis (1997, 2002).

5.1 *Cryptamphorella conara-C. macropora* assemblage zone

The radiolarians of *C. conara- C. macropora* assemblage zone occurred in samples SD75–SD88 collected from the burgundy chert in the top of the Zongzhuo Formation.

Representative species of this zone include: *Archaeodictyomitra* sp., *A. squinaboli*, *A. simplex*, *A. sliteri*, *Cryptamphorella conara*, *C. macropora*, *Dictyomitra* cf. *multicostata*, *D. napaensis*, *D. formosa*, *Theocampe tina*, *Thanarla* aff. *conica*, *Tricolocapsa*(?) sp., *Pseudodictyomitra nakasekoi*, *P. hornatissima*, *P*. sp., *Patulibracchium* cf. *P. davisi* and *Rhopalosyringium elegans.*

Among them, *Archaeodictyomitra* sp., *A. squinaboli*, *A. simplex*, and *A. sliteri* were reported from Upper Cretaceous radiolarian assemblages in the Russian Platform (Vishnevskaya and DeWever, 1998). *Cryptamphorella macropora* was a key species in radiolarian zone from Tu (*Theocampe urna*) to Pa (*Pseudoaulophacus abschnitta*) in Japan (Hollis and Kimura, 2001), which had been interpreted as an age of Turonian to Early Maastrichtian.*Dictyomitra formosa* was stratigraphically limited to the Cenomanian to Campanian. *Dictyomitra napaensis* was common in Santonian to Campanian. *Dictyomitra* cf. *multicostata* was a worldwide species which occured frequent in Upper Cretaceous (Bandini et al., 2006). *Theocampe tina* ranged from Turonian to Early Campanian (Hollis and Kimura, 2001).

Therefore, the age of this radiolarian assemblage zone could be interpreted as Santonian to Early Campanian.

5.2 *Amphisphaera coronate* interval zone

The base of this zone was defined by the first appearance of *Amphisphaera coronata* to the first appearance of *Buryella tetradica*. The top of this zone was coincident with the base of the *Buryella foremanae* zone (Hollis, 1993a) and was characterized by the first occurrence of *Amphisphaera coronata.* This zone was characterized by the dominant species of *Amphisphaera coronata*, *A. macrosphaera*, *Buryella dumitricai*, *B. tetradica*, *Calocycletta tibeta*, *Dictyomitra* aff. *rhadina*, (?)*Orbiculiforma renillaeformis*, *Spongodiscus* sp., *S. rhabdostylus*, *Stylosphaera*(?) *pusilla*, *Haliomma* sp, and *H*(?). *teuria*. These early Paleocene taxa were collected in burgundy, green and gray siliceous shale in the bottom of the Sangdanlin Formation in samples SD181, SD182, SD184 and SD191. Among them, *Amphisphaera macrosphaera* occurred sporadically in the RP1-RP2 and became common in RP4. It was the key specie in radiolarian zone *Buryella granulata* (Hollis, 1997). The *Buryella granulate* Interval Zone had been interpreted as an age of late Danian, early Paleocene (Upper NP3 to Lower NP4). *Calocycletta tibeta* was limited to the early Paleocene of Zheba group by Ding Lin (2003). *Haliomma* sp., *H.* (?) *teuria* andStylosphaera(?) pusilla were common in Paleocene sediments. As above mentioned, this

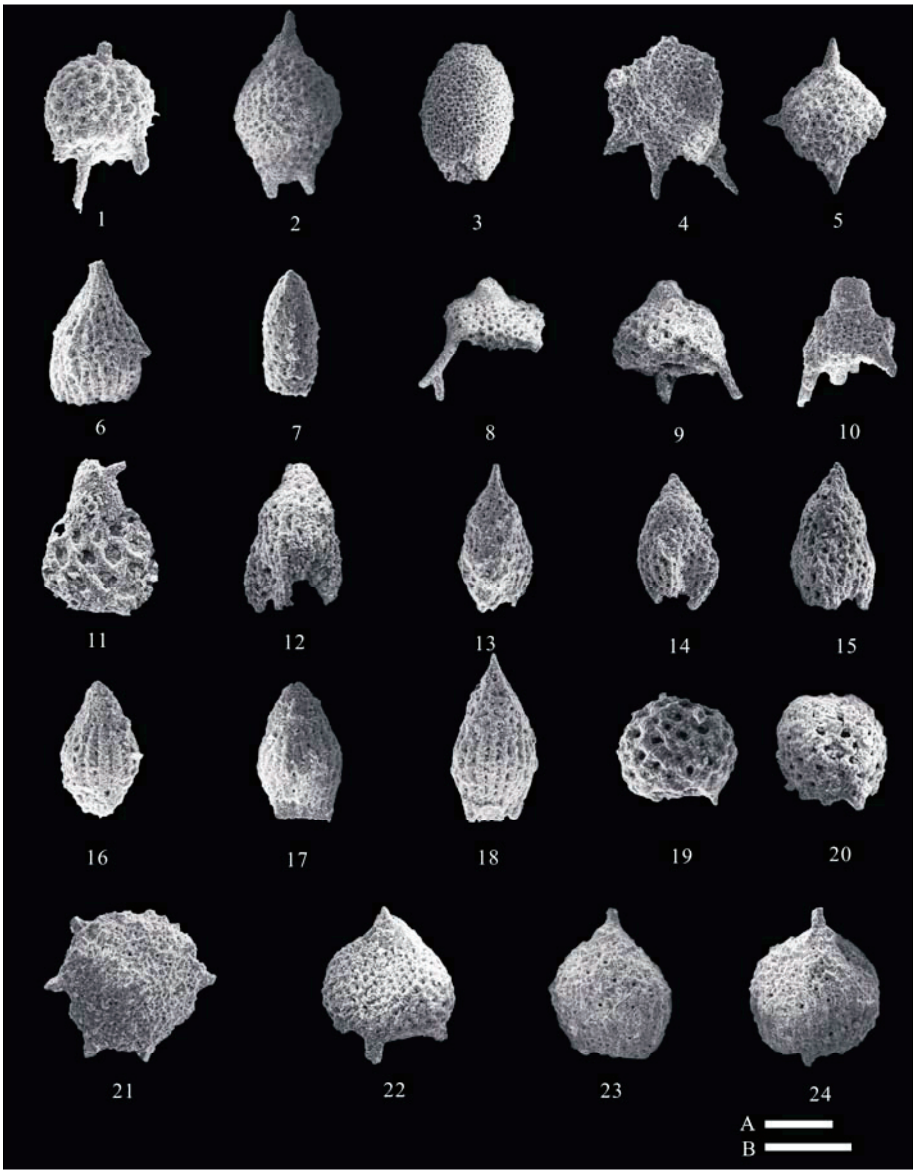

Fig. 4. Scanning electron micrographs of Paleocene-early Eocene radiolarians from the Sangdanlin section.
1, *Dorcadospyris platyacantha* (Ehrenberg), Sample SD236; 2, (?)*Pseudostaurosphaera* sp., Sample SD224; 3, *Spongurus*(?) *regularis* Borisenko, Sample SD224; 4, *Stylotrochus*(?) *nitidus* Riedel et Sanfilippo, Sample SD245; 5, *Spongodiscus rhabdostylus* (Ehrenberg), Sample SD182; 6, *Calocycletta tibeta* Ding, Sample SD181; 7, *Artostrobus pusillum* (Ehrenberg), Sample SD236; 8, *Bekoma bidartensis* Riedel et Sanfilippo, Sample SD240; 9, *Bekoma* sp., Sample SD236; 10, *Bekoma bidartensis* Riedel et Sanfilippo, Sample SD240; 11, *Clathrocycloma*(?) *parcum* Foreman, Sample SD224; 12, *Lithochytris archaea* Riedel et Sanfilippo, Sample SD245; 13, *Phormocyrtis striata exquisite* (Kozlova), Sample SD236; 14, *Phormocyrtis striata exquisite* (Kozlova), Sample SD236; 15, *Phormocyrtis striata striata* (Kozlova), Sample SD245; 16, *Buryella pentadica* Foreman, Sample SD203; 17, *Buryella pentadica* Foreman, Sample SD203; 18, *Buryella tetradica* Foreman, Sample SD236; 19, *Dorcadospyris* sp., Sample SD224; 20, *Dorcadospyris confluens* (Ehrenberg), Sample SD224; 21, *Spongotrochus*(?) *polygonatus* (Campbell and Clark), Sample SD109; 22, *Lychnocanoma bellum* (Clark and Campbell), Sample SD236; 23, *Lamptonium fabaeforme fabaeforme* (Krasheninnikov), Sample SD242; 24, *Lamptonium fabaeforme fabaeforme* (Krasheninnikov), Sample SD242; Scale bar indicates 100 μm, A for figures 2-6, 8-18, 21-24; B for figures 1, 7, 19, 20.

radiolarian zone indicated a Late Danian, Early Paleocene age.

5.3 *Buryella tetradica-Bekoma campechensis* interval zone

The taxa in *Buryella tetradica-Bekoma campechensis* Interval Zone were collected from the samples SD203, SD213, SD224, and SD227 in the middle part of the Sangdanlin Formation. This zone was defined by the FA (first appearance) of *Buryella tetradica* to the LA (last appearance) of *Bekoma campechensis. Buryella tetradica* first appeared approximately at the Early/Late Paleocene boundary at Site 208(mid NP4) (Hollis, 1997). Although only a maximum age limited could be determined for the top of RP5 (lower NP6), it was close to the minimum age limit provided by the FA of *Bekoma campechensis* in tropical and North Atlantic (Foreman 1973a; Nishimura 1987). Common species in this zone included: *Bekoma campechensis*, *Buryella tetradica*, *B. pentadica*, *Clathrocycloma*(?) *parcum*, *C.* aff. *catherinea*,

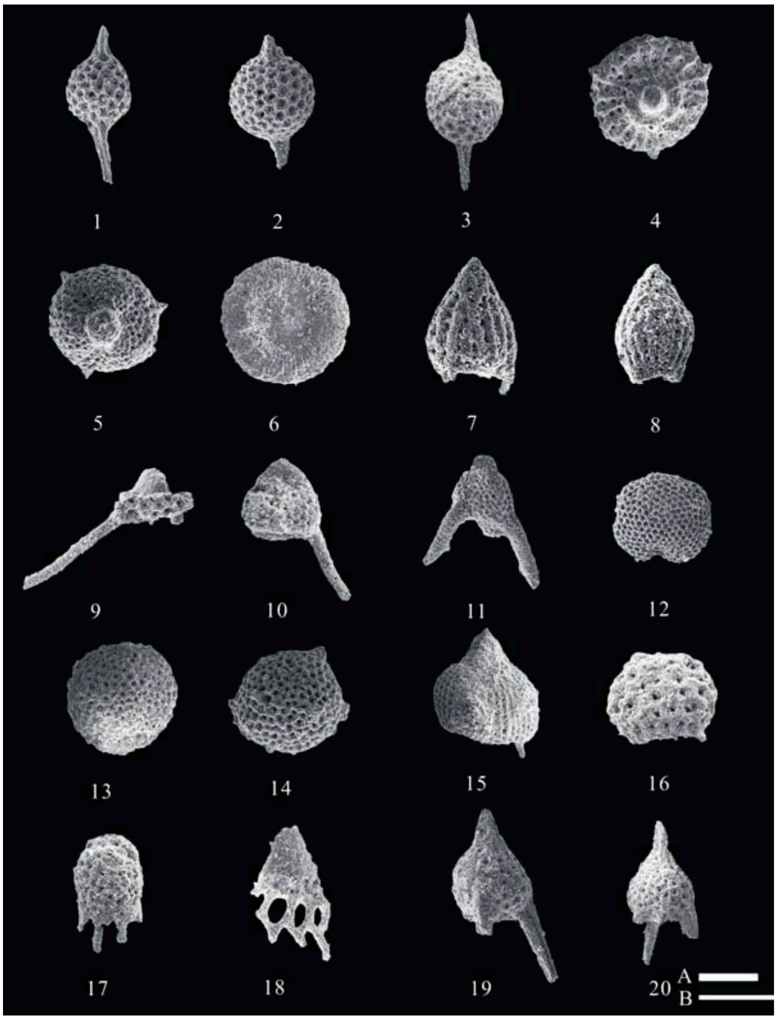

Fig. 5. Scanning electron micrographs of Paleocene-early Eocene radiolarians from the Sangdanlin section II.
1, *Stylosphaera pusilla* (Campbell and Clark), Sample SD181; 2, *Amphisphaera macrosphaera* (Nishimura), Sample SD182; 3, *Amphisphaera coronate* (Ehrenberg), Sample SD182; 4. *Orbula* aff.*ducalis* Foreman, Sample SD224; 5, *Orbula comitata* Foreman, SD203; 6, *Spongodiscus* sp., Sample SD191; 7, *Lychnocanium carinatum* Ehrenberg, Sample SD236; 8, *Buryella tetradica* Foreman, Sample SD236; 9, *Bekoma divaricata* Foreman, Sample SD240; 10, *Bekoma divaricata* Foreman, Sample SD240; 11, *Bekoma campechensis* Foreman, Sample SD224; 12, (?)*Orbiculiforma renillaeformis* (Campbell and Clark), Sample SD181; 13, (?)*Orbiculiforma renillaeformis* (Campbell and Clark), Sample SD181; 14, *Haliomma*(?) *teuria* (Hollis), Sample SD182; 15, *Lychnocanoma costata* Nishimura, Sample SD224; 16, *Dorcadospyris* sp., Sample SD224; 17, *Gorgospyris hexapodalia* Clark and Campbell, SD245; 18,*Clathrocycloma*(?) *parcum* Foreman, Sample SD224; 19, *Lychnocanoma babylonis* Clark and Campbell, Sample SD236; 20, *Lychnocanoma babylonis* Clark and Campbell, Sample SD236; Scale bar indicates 100 μm, A for figures,4-6, 12-15, 19, 20.; B for figures,1-3, 7-11, 16-18.

Dorcadospyris confluens, *D.* sp., *Lychnocanoma costata*, *Mita* cf. *regina*, *Orbula comitata*, *O.* aff. *ducalis*, (?) *Pseudostaurosphaera* sp. and *Spongurus*(?) *regularia*. Among them, *Bekoma campechensis*, *Buryella tetradica*, *B. pentadica*, *O. comitata* and *O.* aff. *ducalis* are the dominant species of the radiolarian Interval zone RP6, which defined by the first morphotypic appearance of *Bekoma campechensis* (Nishimura, 1992). *Spongurus*(?) *regularia* was reported in the northwest Atlantic by Nishimura (1992), which occurred in late Paleocene. Therefore, this radiolarian zone indicated a Selandian to Thanetian age.

5.4 *Bekoma bidartensis - B. divaricata* interval zone

The definition of this zone: Interval from the FA of *Bekoma bidartensis* to the LA of *B. divaricata*. Representative species include: *Artostrobus pusillum*, *B. bidartensis*, *B. campechensis*, *B. divaricata*, *Dorcadospyris platyacantha*, *Gorgospyris hexapodalia*, *Lychnocanuim carinatum*, *Lychnocanoma babylonis*, *L. bellum*, *Lamptonium fabaeforme fabaeforme*, *Lithochytris archaea*, *Phormocyrtis striata exquisite*, *P. s. striata* and *Stylotrochus*(?) *nitidus*, which were collected from samples SD232–248. Among them, *Lychnocanoma babylonis*, *L. costata*, *L. carinatum* had been encountered in the northwest Atlantic, they occurred in Lower part of *Bekoma campechensis* Zone (RP7) (Nishimura, 1992). *Lamptonium fabaeforme fabaeforme* is a common element of the radiolarian zone RP7. The Paleocene/Eocene boundary lied within RP7 zone (Sanfilippo and Nigrini,

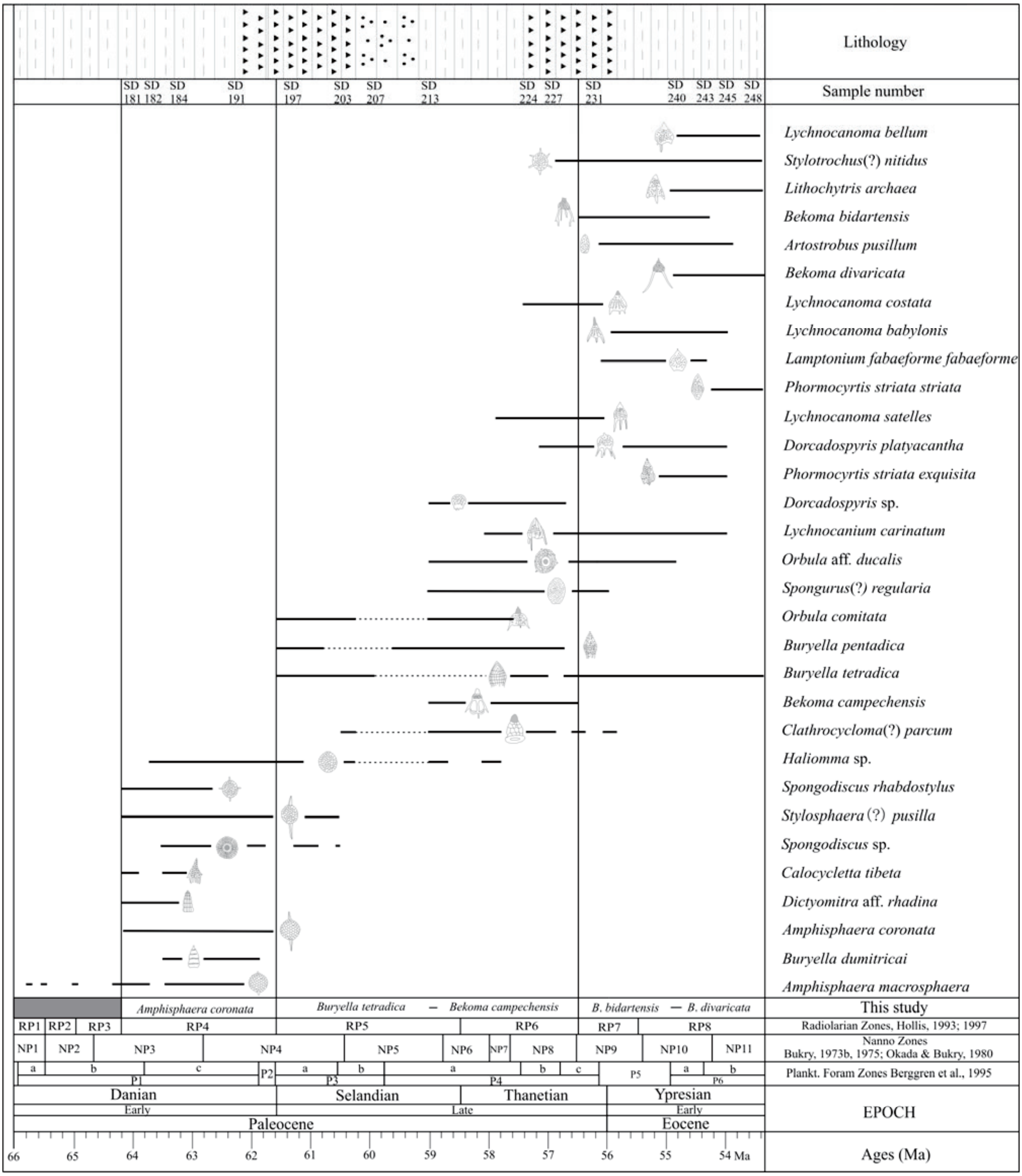

Fig. 6. Ranges of radiolarian key species in Paleocene-lower Eocene strata in the Sangdanlin Formation.

1998a). *P. s. striata* first appeared in lower RP8 in the Mead Stream (Hollis, 1997). *Buryella clinata* had not been encountered in the Sangdanlin section, but elsewhere the top of the *B. clinata* zone (Foreman, 1973a; Nishimura, 1987) was marked by the evolutionary transition from *P. s. exquisita* to *P. s. striata* and the LA of *Bekoma divaricata*. In summary, the zone could roughly be compared with New Zealand radiolarian zone RP7 and RP8 (Hollis, 1997), which had been explained as an age of late Paleocene to early Eocene, containing the Paleocene/Eocene boundary.

6 Discussion

In the present study, we found that well-preserved radiolarian fossils could be obtained from the siliceous shale in the top of the Zongzhuo Formation and the chert and siliceous shale in the middle of the Sangdanlin Formation. Ding Lin (2003) assigned the radiolarian faunas from the Zheba group to the Paleocene zones RP1-RP6. The radiolarian fossils reported by Li Yalin et al. (2007) were difficult to identify because of poor preservation. Hu et al. (2015) used radiolarian and nannofossil biostratigraphy coupled with detrital zircon geochronology to firmly constrain the time when Asian-derived detritus was first deposited in India in the Sangdanlin section. The radiolarian fauna could be assigned to the Paleogene radiolarian zones RP4–6. By comparison with the Paleocene radiolarian zones of the North Atlantic and the South Pacific, Wang Xueheng et al. (2016) reassigned the radiolarian zone RP6, containing *Bekoma campechensis* and *B. bidartensis*, from the Selandian to the latest Thanetian. Compared with previous studies (Ding Lin, 2003; Chan, 2006; Li Yalin et al., 2007; Hu et al, 2015; Wang Xueheng et al., 2016), the new radiolarian zone, the *Bekoma bidartensis-B. divaricata* Interval Zone, which has an equivalent age range with RP7-RP8 (late Paleocene to early Eocene, about 53.6–56 Ma) (Hollis, 1997), was identified in the Sangdanlin Formation in this paper. The radiolarian *Bekoma divaricate* is the index species of the *Bekoma divaricate* Interval Zone (Hollis, 1997) and the key species *Phormocyrtis striata striata*, *P. s. exquisite* in this zone, was found in the chert in the middle of the Sangdanlin Formation. *B. divaricate*is restricted to specimens having three cylindrical, slender feet that generally curve distally outwards and no branches on the distal portion.

6.1 Radiolarian paleoecological setting

Radiolarian planktonic protozoa are widely distributed in oceans from the surface to the bottom. The most important ecological characteristic of the radiolaria is their vertical distribution. At greater depths, the fauna were impoverished, but different assemblages of polycystine species appeared to inhabit various depths from 0 to 5000 m (DeWever et al., 2001). Abelmann and Gowing (1997) reported that the distribution of individual radiolarian assemblages was controlled by specific hydrographic conditions and water depth; the comparison of living polycystine radiolarian taxa with those preserved in sediments showed general similarities. According to the data from both the water-column and surface sediments of the Japan sea, the depth distribution of radiolarians was summarized by Takuya (2002) as follows: subsurface-water and intermediate-water species are abundant in 40–-300 m depths; the main radiolarians in this range are Spumallaria. When the depth of the water reaches 1000–2000 m, the abundance and diversity of Nassellarias increases rapidly and dominates the deep-water species. Chen Muhong and Tan Zhiyuan (1996) indicated that the quantity of Nassellarias bearing three feet as extensions of spines increases rapidly in the 1500 m depth range.

The main characteristic of late Cretaceous radiolarian fauna in the burgundy siliceous shale and chert of the Zongzhuo Formation is *Crytamphorella* and other spherical Spumallarias. Therefore, it has been suggested that the top of the Zongzhuo Formation deposited in hemipelagic and outer shelf to slope conditions,

The dominant generas of the radiolarian fauna identified in the Sangdanlin Formation included *Bekoma*, *Buryella*, *Lamptonium*, *Lychnocanoma*, *Orbula*, and *Phormocyrtis*. Of these, *Bekoma*, *Lamptonium*, *Lychnocanoma*, and *Orbula* belong to the order Nassellarias and bear three feet. It was observed in thin sections of the radiolarian-bearing siliceous rocks that the radiolarian fossil accounts for approximately 80% of the whole rock, and there is no quartz, feldspar, or other terrestrial detritus (Fig. 2e). Therefore, this indicates the development of a set of deep marine sediments (Sangdanlin Formation) in the northern subzone of the Tethyan Himalaya between Paleocene and early Eocene (~53.6 Ma).

6.2 Tectonic setting and timing of the India-Asia collision

Whether the strata in the Sangdanlin section were deposited on continental lithosphere or oceanic crust is a long-debated but important issue. If deposited on oceanic lithosphere, this would indicate a significant separation from the Indian continental lithosphere, and the Sangdanlin section would predate collision (DeCelles et al., 2014). We provide evidence through lithology and biostratigraphy to support the interpretation that the Sangdanlin section's record resulted from the initial India-Asia collision.

As stated above, researchers have different views on the age, stratigraphy, and tectonic attributes of sedimentation in the Sangdanlin section (Li Xianghui et al., 2001; Ding et al., 2005; Wang et al., 2011; DeCelles et al., 2014; Hu et al., 2015). The Sangdanlin section is divided into three formations, Zongzhuo, Sangdanlin, and Zheya, based on lithological characteristics. The late Cretaceous Zongzhuo Formation is dominated by shale, siliceous shale, chert, lithic sandstone, and quartzose sandstone. Radiolaria yielded from the burgundy siliceous shales and cherts of the Zongzhuo Formation were recognized as belonging to the zone *Cryptamphorella conara-C. macropora* and interpreted as to date to the Santonian to Early Campanian. The detrital zircons from the litharenite within the Zongzhuo Formation have the same U-Pb age pattern as those from quartzarenites from the northern part of the

Indian continent (Hu et al., 2010; Wang et al., 2011; DeCelles et al., 2014). The bottom of the Zongzhuo Formation included hemipelagic foraminifera-bearing limestones and pebbly-to-coarse-grained sandstone turbidites deposited along or at the base of the north-facing continental slope of the northern Indian passive continental margin, which suggested a short distance of transport from the nearby Indian cratonic margin and the Zongzhuo Formation (Fig. 7a) (Ding Lin, 2003; Wang et al., 2011).

The major lithology of the Sangdanlin Formation includes the following: variegated (burgundy, green, and gray) siliceous laminated shale; radiolarian chert; and lithic quartzose sandstone. Three Paleocene to early Eocene radiolarian zones are mainly from the green, gray siliceous shale and radiolarian chert, with a small amount from the burgundy siliceous shale. The lithologic and paleontologic features of the Sangdanlin Formation indicate that the Sangdanlin Formation should be deposited in a deep marine environment (Ding et al., 2005; Wang et al., 2011). The Zheya Formation, conformably overlying the Sangdanlin Formation, is characterized by dark gray carbonaceous shale intercalated with medium-to coarse-grained lithic sandstone beds, chert, and volcanics. Biostratigraphic age control is lacking. However, considering that it conformably overlies the Sangdanlin Formation, it is unlikely to be younger than the youngest marine strata documented in the Tethyan Himalaya (Wen Shixuan, 1987a, 1987b; Willems et al., 1996). Lithic-rich detrital composition, deep-marine turbidites, and an upward-coarsening trend within the Sangdanlin and Zheya formations are typical features of foredeep basin deposits

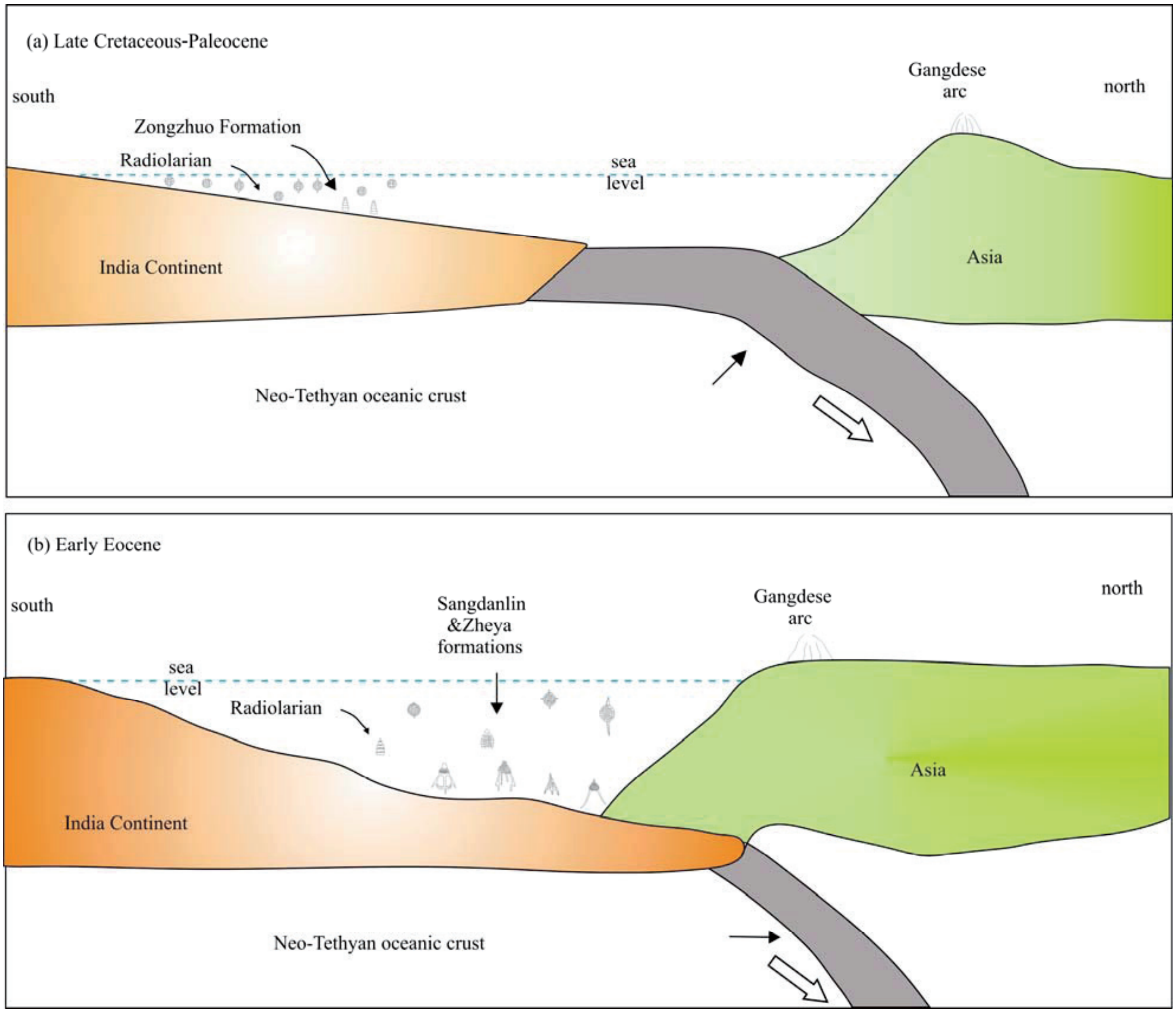

Fig. 7. Two contrasting tectonic models that can explain paleogeographic setting of the Sangdanlin aera during different time frames, from Late Cretaceous to early Eocene.

(a), The Zongzhuo Formation deposited at the base of the north facing continental slope of the northern Indian passive continental margin, pre collision ;
(b), The Sangdanlin and Zheya formations deposited in the Himalayan foreland basin, arrival of Asian detritus onto Indian margin, syn-collision.

(Sinclair, 1997; Wang et al., 2011). We interpreted the Sangdanlin and Zheya formations as having been deposited in the Himalayan foreland basin directly on the Indian passive margin, which excludes the possibility of the existence of a remnant oceanic basin (Fig. 7b). Deposition records showing the transition from the Zongzhuo Formation to the Sangdanlin and Zheya formations indicate the southward obduction of ophiolitic materials onto the northern Indian margin and provide a minimum age constraint for the timing of the India-Asia continental collision.

7 Conclusions

The strata of the Sangdanlin section is divided into three lithostratigraphic units which are from bottom to top: (1) the Zongzhuo Formation mainly composed of lithic sandstone, shale and quartzose sandstone; (2) the Sangdanlin Formation dominated by chert and siliceous shale; and (3) the Zheya Formation characterized by flysch. The upper Cretaceous Zongzhuo Formation was deposited on the Greater Indian passive continental margin. The Paleocene-early Eocene Sangdanlin and Zheya were deposited in a foreland basin.

The radiolarian faunas from the Zongzhuo and Sangdanlin formations in the Sangdanlin sectionare assigned in ascending to the *Cryptamphorella conara*–*C. macropora* Assemblage Zone, *Amphisphaera macrosphaera* Interval Zone, *Buryella tetradica*–*Bekoma campechensis* Interval Zone and *Bekoma campechensis*–*B. divaricata* Interval Zone. The *B. bidartensis*–*B. divaricata* Interval Zone is the youngest radiolarian zone which has an equivalent age range (late Paleocene to early Eocene) with RP7–RP8 (Hollis, 1997).

Major changes in provenance occurred at the boundary between the Zongzhuo Formation and the Sangdanlin Formation. The early Eocene radiolarian fauna in the Sangdanlin Formation constrain the age of initial collision between India and Asia to no later than 53.6 Ma.

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References

Abelmann, A., and Gowing, M.M., 1997. Spatial distribution pattern of living polycystine radiolarian taxa–baseline study for paleoenvironmental reconstructions in the Southern Ocean (Atlantic sector). *Marine Micropaleontology*, 30: 3–28.

Aitchison, J. C., Ali, J.R., and Davis, A.M., 2007. When and where did India and Asia collide? *Journal of Geophysical Research*:*Solid Earth*, 112: B05423.

Bandini, A.N., Baumgartner, P.O., and Caron, M., 2006. Turonian radiolarians from Karnezeika,Argolis Peninsula, Peloponnesus (Greece).*Swiss Journal of Geosciences*., 99 (1): S1–S20.

Blondeau, A., Bassoullet, J.P.; Colchen, M., Han, T.L., Marcoux, J., Mascle, G., and Van Haver, T., 1986. Disparition des Formations Marines a L'Eocene Inferieur en Himalaya. Evolution des domaines orogeniques d'Asie meridionale (de la Turquie a L. Indonesic), Volume Memoire 47: Nancy, Sciences de la Terre, 103–111.

Cai Fulong, Ding Lin and Yue Yahui, 2011. Provenance analysis of upper Cretaceous strata in the TethysHimalaya,southern Tibet: implications for timing of India–Asia collision. *Earth and Planetary Science Letters*., 305 (1–2): 195–206.

Cai Fulong, Ding Lin, Leary, R.J., Wang Houqi, Xu Qiang, Zhang Liyun and Yue Yahui, 2012. Tectonostratigraphyand provenance of an accretionary complex within the Yarlung–Zangpo suturezone, southern Tibet: Insights intosubduction–accretion processes in the Neo–Tethys. *Tectonophysics*, 574–575: 181–192.

Chan, G.H.N., Aitchison, J.C., Crowley, Q.G., Horstwood, M.S.A., Searle, M.P., Parrish, R.R., and Chan, J.S.–L., 2015. U–Pb zircon ages for Yarlung Tsangpo suture zone ophiolites, southwestern Tibet and their tectonic implications. *Gondwana Research*, 27: 719–732.

Chan, S.L., 2006. *Paleocene deep–matine sediments in southern central Tibet: Indication of an arc–continent collision*. Hong kong: University of Hong Kong (Master of Philosophy thesis): 1–201.

Chen Muhong and Tan Zhiyuan, 1996. *Radiolaria in Sediments from the Middle and Northern South China Sea*. Beijing: Science Press, 1–271(in Chinese).

De Wever, P., Dumitrica, P., Caulet, J.P., Nigrini, C., and Caridroit, M., 2001. *Radiolarians in the sedimentary record*. Amsterdam: Gordon and Breach Science Publishers, 1–533.

DeCelles, P.G., Kapp, P., Gehrels, G.E., and Ding Lin, 2014. Paleocene–Eocene foreland basin evolution in the Himalaya of southern Tibet and Nepal: implications for the age of initial India–Asia collision. *Tectonics*, 33, 824–849.

Ding Lin, 2003. Paleocene deep–water sediments and radiolarian fauna: Implications for evolution of Yarlung Zangbo foreland basin, southern Tibet. *Science in China Series D: Earth Sciences*, 33, 47–58.

Ding Lin, Kapp, P., and Wan Xiaoqiao, 2005. Paleocene–Eocene record of ophiolite obduction and initial India–Asia collision, south central Tibet. *Tectonics*., 24: 1–18.

Foreman, H.P., 1973a. Radiolaria of Lge 10 with systematics and ranges for the families Amphipyndacidae, Artostrobiidae, and Theoperidae. *Initial Reports of the Deep Sea Drilling Project*. Washington, D.C.: U.S. Government Printing Office, 10: 407–474.

Foreman, H.P., 1973b. Radiolaria from DSDP Leg20. *Initial Reports of the Deep Sea Drilling Project*. Washington, D.C.: U.S. Government Printing Office, 20: 249–305.

Foreman, H.P., 1975. Radiolaria from the North Pacific, Deep Sea Drilling Project, Leg 32. In: Larson, R.L., Mpberly, R., et al. (eds.), *Initial Reports of the Deep Sea Drilling Project*, 32: 579–676.

Foreman, H.P., 1977. Mesozoic Radiolaria from the Atlantic Basin and its borderlands. *Developments in Palaeontology and Stratigraphy*, 6: 305–320.

Garzanti, E., Baud, A., and Mascle, G., 1987. Sedimentary record of the northward flight if India and its collision with Eurasia (Ladakh Himalaya, India). *Geodinamica Acta*, 1(4–5): 297–312.

Hollis, C.J., 1993a. Latest Cretaceous to Late Paleocene radiolarian biostratigraphy: A new zonation from the New Zealand region. *Marine Micropaleontology*, 21: 295–327.

Hollis, C.J., 1997. *Cretaceous–Paleocene Radiolarian from eastern Marlborough, New Zealand*. Lower Hutt, New Zealand: Institute of Geological and Nuclear Sciences Limited, 152.

Hollis, C.J., 2002. Biostratigraphy and paleoceanographic significance of Paleocene radiolarians from offshore eastern New Zealand. *Marine Micropaleontology*, 46(3–4): 265–316

Hollis, C.J., and Kimura, K., 2001.Aunified radiolarian zonation for the Late Cretaceous and Paleocene of Japan. *Micropaleontology*, 47(3): 235–255.

Hu Xiumian, Jansa, L., Chen Lei, Griffin, W.L., O'Reilly, S.Y., and Wang Jiangang, 2010. Provenance of lower cretaceous Wlong volcaniclastics in the Tibetan Tethyan Himalaya: implicationsfor the final breakup of Eastern Gondwana. *Sedimentary Geology*, 223: 193–205.

Hu Xiumian, Sinclair, H.D., Wang Jiangang, Jiang Hehe and Wu Fuyuan, 2012. Late Cretaceous–Palaeogene stratigraphic and basin evolution in the Zhepure Mountain of southern Tibet: implications for the timing of India–Asia initial collision. *Basin Research*, 24(5): 520–543.

Hu Xiumian, Garzanti, E, Moore, T., and Raffi, I., 2015. Direct stratigraphic dating of India–Asia collision onset at the Selandian (middle Paleocene, 59±1 Ma). *Geology*, 43(10): 859–862.

Hu Xiumian, Garzanti, E., Wang jiangang, Huang Wentao, An Wei and Webb, A., 2016. The timing of India–Asia collision onset–Facts, theories, controversies. *Earth–Science Reviews*, 160: 264–299

Jadoul, F., Berra, F., and Garzanti, E., 1998. The Tethys Himalayan passive margin from late Triassic to early Cretaceous (South Tibet). *Journal of Asian Earth Science*, 16: 173–194.

Li Guobiao, Wan xiaoqiao, Liu Wencan, Liang Dingyi and Yun Hyesu, 2005. Discovery of Paleogene marine stratum along the southern side of Yarlung Zangbo suture zone and its implications in tectonics. *Science in China Series D: Earth Sciences*, 48: 647–661.

Li Guobiao, Jiang Ganqing and Wan Xiaoqiao, 2011. The age of the Chuangde Formation in Kangmar, southern Tibet of China: implications for the origin of Cretaceous Oceanic Red Beds (CORBs) in the Northern Tethyan Himalaya. *Sedimentary Geology*, 235: 111–121.

Li Hongsheng, 2000. Discovery of Paleogene radiolarian in South Tibet: A late report of discovery. *Proceedings of the Third National Stratigraphical Conference of China*. Beijing: Science Press, 125–136 (in Chinese).

Li Xianghui, Wang Chengshan and Hu Xiumian, 2001. Latest non–carbonate marine sediment in Tibet: significance to closure of the Neo–Tethys Sea. *Acta Geologica Sinica*, 75(3): 314–321 (in Chinese with English abstract).

Li Yalin, Wang Chengshan, Hu xiumian, Bak, M., Wang jinjun and Chen lei, 2007. Characteristics of Early Eocene radiolarian assemblages of the Saga aera, southern Tibet and their constraint on the closure history of the Tethys. *Chinese Science Bulletin*, 52(15): 2108–2114.

Liang Yinping, 2012. *Cretaceous–Paleocene radiolarian fauna in Saga–Zhongba, southwestern Tibet: implications for the evolution of Neo–Tethys*. Wuhan: China University of Geosciences (Ph. D thesis): 1–105 (in Chinese).

Liu Jianbing and Aitchison, C.J., 2002. Upper Paleocene radiolarians from the Yamdrok melange, south Xizang (Tibet), China. *Micropaleontology*, 48: 145–154.

Liu Jianguo, Hattori Keiko and Wang jian, 2017. Mineral inclusions in chromite from the chromite deposit in the Kudi ophiolite, Tibet, Proto–Tethys. *Acta Geologica Sinica* (English Edition), 91(2): 469–485.

Lowe, D.R., 1982. Sediment gravity flows: Ⅱ. Depositional models with special reference to deposits of high–density turbidity currents, *Journal of Sediment Research*, 33(6): 279–297.

Mutti, E., 1992. *Turbidite Sandstones*. Parm: Italy. Azienda Generale Italiana Petroli, 275.

Najman, Y., Appel, E., Boudagher–Fadel, M., Bown, P., Carter, A., Garzanti, E., Godin, L., Han,J., Liebke, U.,Oliver, G., Parrish, R. and Vezzoli, G., 2010. Timing of India–Asia collision: geological, biostratigraphic, and palaeomagnetic constraints. *Journal of Geophysical Research*, *Solid Earth*, 115(115): 1–70.

Newman, W.A., 1994. Atlas of Mesozoic and Cenozoic coastlines. *Journal of Experimental Marine Biology and Ecology*, 183(2): 301–302.

Nishimura, A., 1987. Cenozoic radiolaria in the western North Atlantic, Site 603, Leg 93 of the Deep Sea Drilling Project. *Initial Reports of the Deep Sea Drilling Project*. Washington, D.C.: U.S. Government Printing Office, 713–737.

Nishimura, A., 1992. Paleocene radiolarian biostratigraphy in the northwest Atlantic at Site 384, Leg 43, of the Deep Sea Drilling Project. *Micropaleontology*, 38: 317–362.

O'Dogherty, L., 1994. Biochronology and paleontology of mid–Cretaceous radiolariansfrom northern Apennines (Italy) and Betic Cordillera (Spain). *Mémoires de Géologie21*, Université de Lausanne, 415.

Patriat, P., and Achache, J., 1984. India–Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates. *Nature*, 311(5987), 615–621.

Pessagno, E.A., and Newport, R.L., 1972. Atechnique for extracting Radiolaria from radiolarian cherts. *Micropaleontology*, 18(2): 231–234.

Pessagno, E.A., 1976. Radiolarian zonation and stratigraphy of the Upper Cretaceous portion of the Great Balley Sequence, California Coast Ranges. *Micropaleontology Special Publication*, 2: 1–95.

Riedel, W.R., and Sanfilippo, A., 1970. Radiolaria, Leg 4, Deep Sea Drilling project. *Initial Reports of the Deep Sea Drilling Project*. Washington, D.C.: U.S. Government Printing Office, 4: 503–575.

Riedel, W.R., and Sanfilippo, A., 1971. Cenozoic Radiolaria from the western tropical Pacific, Leg 7. *Initial Reports of the Deep Sea Drilling Project*. Washington, D.C.: U.S. Government Printing Office, 7(2): 1529–1672.

Riedel, W.R., and Sanfilippo, A., 1978. Stratigraphy and evolution of tropical Cenozioc radiolarians. *Micropalcontology*. 18(2): 231–234.

Rowley, D.B., 1996. Age of initiation of collision between India and Asia: A review of stratigraphic data, *Earth Planet*, 145: 1–13.

Rowley, D.B., 1998. Minimumage of initiation of collision between India and Asia north ofEverest based on thesubsidence history of the Zhepure Mountain section. *The Journal of Geology*, 106(2): 229–235.

Sanfilippo, A., and Riedel, W.R., 1973. Cenozoic Radiolaria (exclusive of theoperids, artostrobiids and amphipyndacids) from the Gulf of Mexico, DSDP Leg 10. *Initial Reports of the Deep Sea Drilling Project*. Washington, D.C.: U.S. Government Printing Office, 10: 475–611.

Sanfilippo, A., and Riedel, W.R., 1985. Cretaceous Radiolarian. In: Bolli, H.M., Saunders, J.B., and Perch–Nielsen, K. (eds.), *Plankton Stratigraphy*. Cambridge University Press, 573–630.

Sanfilippo, A., and Nigrini, C., 1998b. Code numbers for Cenozoic low latitude radiolarian biostratigraphic zones and GPTS conversion tables. *Marine Micropaleontology*, 33(1/2): 109–156.

Sanfilippo, A., and Nigrini, C., 1998a. Upper Paleocene–lower Eocene deep–sea radiolarian stratigraphic and the Paleocene/ Eocene series boundary. In: Aubry, M.P., Lucas, S.G., and Berggren, W.A. (eds.), *Late Paleocene–early Eocene climatic and biotic evolution*. New York: Columbia University Press, 244–276.

Sanfilippo, A., and Hull, D.M., 1999. Upper Paleocene–Lower Eocene Radiolarian biostratigraphy of the San Francisco de Paula Section, Western Cuba: regional and global comparisons. *Micropaleontology*, 45(5): 1286–1301.

Searle, M., 1986. Structural evolution and sequence of thrusting in the High Himalayan,Tibetan—Tethys and Indus suture zones of Zanskar and Ladakh, Western Himalaya.*Journal of Structural Geology*., 8 (8): 923–936.

Sheng Jinzhang, 1976. Radiolarian faunas of Gyirong group in the Qomolangma region. *Report of the Scientific Expedition to the Qomolangma region* (1966–1968), *Paleontology* (second fascicule). Beijing: Science Press, 125–136 (in Chinese).

Takuya, I., 2003. Depth–related radiolarian assemblage in the water–column and surface sediments of the Japan Sea. *Marine Micropaleontology*, 47: 253–270.

Vishnevskaya, V.S., and DeWever, P., 1998. Upper Cretaceous radiolaria from the Russian Platform. *Revue deMicropaleontologie*, 41(3): 235–265.

Wan Xiaoqiao and Ding lin, 2002. Discovery of the latest Cretaceous planktonic foraminifera from Gyirong of southern Tibet and its chronostratigraphic significance. *Acta Palaeontologica Sinica*, 41(1): 89–95 (in Chinese with English abstract).

Wang Jiangang, Hu Xiumian and Huang Zhicheng, 2008. Provenance Analysis of Late Cretaceous–Early Eocene Sandstones in the Sangdanlin Area, Southern Tibet. *Acta Geologica Sinica*, 82(1): 92–103 (in Chinese with English abstract).

Wang Jiangang, Hu Xiumian, Luba J and Huang Zhicheng, 2011. Provenance of the Upper Cretaceous–Eocene Deep–Water Sandstones in Sangdanlin, Southern Tibet: Constrains on the Timing of Initial India–Asia Collision. *The Journal of Geology*, 119: 293–309.

Wang Xueheng, Luo Hui, Xu Bo, Zhu Youhua, Chen Dishu and Liu Shijia, 2016. Upper Paleocene radiolarian fauna from the Sangdanlin section, southern Tibet, China and its geological significance. *Acta Micropalaeontologica Sinica*, 33(2): 105–126 (in Chinese with English abstract).

Wen Shixuan, 1987a. Cretaceous system**.** *Stratigraphy of the Mount Qomolangma Region*. Beijing: Science Press, 130–159 (in Chinese).

Wen Shixuan, 1987b. Tertiary system**.** *Stratigraphy of the Mount Qomolangma Region*. Beijing: Science Press, 160–180 (in Chinese).

Willems, H., Zhou Zhongyi, Zhang Binggao and Grafe, K.U.,1996, Stratigraphy of the upper Cretaceous andLower Tertiarystrata in the Tethyan Himalayas ofTibet (Tingri area, China), *International Journal of Earth Sciences*, 85: 723–754.

Wu Fuyuan, Ji Weiqiang, Wang Jiangang, Liu Chuanzhou, Chung Sunlin and Clift, P.D., 2014. Zircon U–Pb and Hf isotopic constraints on the onset time of India–Asia collision. *American Journalof Science*, 314: 548–579.

Wu Zhenhan, Zhao Zhen, Patrick J. Barosh and Ye Peisheng, 2016. Early Cretaceous tectonics and evolution of the Tibetan Plateau. *Acta Geologica Sinica* (English Edition), 90(3): 847–857.

Xu Zhiqin, Dilek, Y., Yang Jingsui, Liang Fenghua, Liu Fei, Ba Dengzhu, Cai Zhihui, Li Guangwei, Dong Hanwen and Ji Shaocheng, 2015. Crustal structure of the Indus–Tsangpo suture zone and its ophiolites in southern Tibet. *Gondwana Research*, 27: 507–524.

Xu Zhiqin, Wang Qin, Li Zhonghai, Li Huaqi, Cai Zhihui. Liang Fenghua, Dong Hanwen, Cao Hui, Chen Xijie, Huang Xuemeng, Wu Chan and Xu Cuiping, 2016. Indo-Asian collision: Tectonic transition from compression to strike slip. *Acta Geologica Sinica*, 90(1): 1–23 (in Chinese with English abstract).

Yin, A., and Harrison, T.M., 2000. Geologic evolution of the Himalaya–Tibetan orogen. *Annual Review of Earth and Planetary Sciences*, 28: 211–280.

Zhang Chang, Liu Chuanzhou, Wu Fuyuan, Zhang Liangliang and Ji Weiqiang, 2016. Geochemistry and geochronology of mafic rocks from the Luobusa ophiolite, South Tibet. *Lithos*, 245: 93–108.

Zhu Bin, Kidd, W.S.F., Rowley, D.B., Currie B.S., and Shafique, N., 2005. Age of initiation of the India–Asia collision in the east–central Himalaya. *The Journal of Geology*, 106(3): 2005.

About the first author:

WANG Tianyang, male; born in 1991 in Kaifeng City, Henan Province. He is currently a Ph. D candidate at the School of Earth Sciences and Resources, China University of Geosciences, and majors in Paleontology and Stratigraphy. Email: guess19911029@163.com; phone: 18600168100.