The youngest marine deposits preserved in southern Tibet and disappearance of the Tethyan Ocean

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ABSTRACT

Fossil ages as young as Priabonian (38–34 Ma) are reported for the last marine sedimentary rocks in southern Tibet. Correlation is based on examination of foraminifers and nannofossil biostratigraphy of youngest preserved sediments in sections at Gamba (Zongpu), Tingri (Qumiba) as well as a previously unreported section at Yadong. Our results demonstrate that a marine seaway remained in existence south of the Yarlung Tsangpo suture zone until at least Priabonian time. Notably this remains a maximum age estimate in this area as all sections are truncated by erosion or faulting. We compare our results with sections throughout the Himalaya region to demonstrate that shallow marine conditions existed widely during the Eocene period. In fact, it seems likely that the marine conditions in the Tethyan Himalaya did not entirely disappear by the end of Priabonian, especially in the eastern Himalaya. The data presented in this study place direct constraints on the elimination of the Tethyan Ocean and thus have important implications for timing of the India–Eurasia collision.

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1. Introduction

The collision of India with Eurasia, which has profoundly influenced the geological, geochemical, climatic and oceanographic evolution of the Earth, is one of the most significant tectonic events during the Cenozoic (Butler, 1995). In the last few decades, many researchers have attempted to reconstruct the evolution of the Himalayan orogen and Tibetan uplift. However, timing of the initiation of continental collision, key to all reconstruction models, is still strongly disputed, and the estimated time ranges from 70 Ma to 25 Ma (Searle et al., 1987; Beck et al., 1995; Yin and Harrison, 2000; Zhu et al., 2005; Aitchison et al., 2007, 2011; Aitchison and Ali, 2012; van Hinsbergen et al., 2012; Wang et al., 2012; Singh, 2013; Xu et al., 2015).

Many approaches are used to date the timing of the collision including the relative position of the Indian plate, the commencement of the influx of sedimentary detritus onto the Indian passive plate margin along the Indus Yarlung Tsangpo Suture Zone (YTSZ), initiation of major collision related thrust systems in the Himalaya Ranges, and the end of calc-alkaline magmatism along the Trans-Himalayan batholith, etc. (Searle et al., 1988; Aitchison et al., 2007; Najman et al., 2010). The cessation of marine sedimentation on the Indian margin, which is closely related to the elimination of the Tethyan Ocean, is widely regarded as placing a direct constraint on timing of the initiation of continent–continent collision and has long been investigated in different Himalayan regions (Rowley, 1996; Green et al., 2008).

In the Lesser Himalaya, the final marine deposits are commonly preserved as part of a nappe or klippe. They commonly underlie regional hiatus and are themselves thrust over Oligocene to Miocene continental clastic sediments. The age of the final marine deposits varies from west to east. In the frontal region of the Kashmir syntaxis, the marine Patala Formation has been dated at 55–50 Ma where it underlies the continental Balakot Formation (Najman et al., 2001, 2002). Southeast of the Kashmir syntaxis, the Subathu Formation outcrops widely in locations from Simla to Tansen (Fig. 1a), and preserves the Eocene final marine deposits of 44 Ma (Bhatia and Bhargava, 2006). South of the eastern Himalayan syntaxis, the collision-related final marine sediments outcrop as the lower Eocene Rengging Formation and the upper lower Eocene to Middle Eocene Yinkiang Formation in the Siang window region of Assam–Arakan Basin (Tripathi et al., 1978, 1981; Tripathi and Mamgain, 1986; Tripathi et al., 1988; Acharya, 2007; Acharya and Saha, 2008). Even younger final marine deposits occur in the Bengal basin, where the Sylhet limestone and overlying Kopili Formation are of Middle to upper Eocene age (Samanta, 1965, 1968, 1969; Singh and Prapat, 1983; Alam et al., 2003).

In the western Tethyan Himalaya, limestone of the Kong Formation (48.6 Ma) in the Zanskar Basin and nummulitic limestone (50.8–49.4 Ma) that outcrop near the Indus Suture Zone are regarded as the
youngest record of the Tethyan Sea (Searle et al., 1988; Green et al., 2008; Mathur et al., 2009). However, it must be noted that nummulitic limestones in the Zanskar valley are overlain by unfossiliferous mass flow deposit (turbidites and deep marine conglomerates) that nevertheless indicate ongoing marine conditions. In southern Tibet, several sedimentary successions containing final marine sediments have been reported, including the Tingri (Qumiba) section (Li et al., 2000; Xu, 2000; Wang et al., 2002; Zhu et al., 2005) and the Gamba (Zongpu) section (Wan, 1987; Willems, 1993; Li and Wan, 2003; Wan et al., 2006, 2010). However, documentation of these sections is commonly incomplete or important questions remain regarding stratigraphic continuity, the reliability of fossil identifications and their depositional setting. In this study, we critically assess existing data of the youngest marine strata in Gamba–Tingri region in order to correlate and compare between sections in southern Tibet. This also includes the Yadong section, a previously unreported succession 70 km east of Gamba, from which we recorded planktonic foraminifers and nannofossils. We endeavor to establish the precise timing of final marine sedimentation in the eastern Tethyan Himalaya, so that we can correlate it with the results from other regions throughout the Himalaya to reconstruct the elimination of the Tethyan Ocean.

2. Geological setting

From south to north, the Himalaya is divided into four zones: the Outer or Sub-Himalaya, the lesser or lower Himalaya, the Greater or Higher Himalaya, and the Tethyan or Tibetan Himalaya. Farther north lies the Indus Yarlung Tsangpo Suture Zone beyond which is the Trans-Himalayan (Gangdese) batholith, or Lhasa Terrane, which represents the original southern margin of Asia prior to Indus collision (Thakur, 1992; Yin, 2006). The Sub-Himalaya, mainly consist of the Neogene Siwalik molasse, bounded by the Main Boundary Thrust (MBT) to the north and the Main Frontal Thrust (MFT) to the south. The Lesser Himalaya consists of low-grade metasedimentary rocks, with discontinuous exposures of Paleogene sediments (Yin, 2006; Acharyya, 2007). The Greater Himalaya, separated from the Lesser Himalaya by the Main Central Thrust (MCT), mainly contains metasedimentary rocks ranging in age from Proterozoic to Ordovician and affected by Oligo–Miocene Himalayan metamorphism. The Tethyan Himalayan zone is separated from the Greater Himalaya across the South Tibetan Detachment Surface (STDS). Paleozoic to Paleogene marine sediments are widely exposed in the Tethyan Himalaya. The Cenozoic pre-collision related Tethyan Himalayan sequence varies between
locations and indicates a northward-deepening environment from continental shelf to slope. In the northern part of Tethyan Himalaya, the sequences are mainly composed by deformed mélangé with conglomerates, cherts and sandstones (e.g. Saga–Gyangze belt, Zanda area) (Liu and Einsele, 1994; Ding et al., 2005; Wan et al., 2014). The shelf deposits are mainly preserved in the Gamba–Tingri region of the eastern Tethyan Himalaya, which is the focus of this study.

The Gamba–Tingri region is located in southern Tibet and lies around 100 km south of the Yarlung Tsangpo Suture Zone (YTSZ). Gamba is located about 90 km SE of Tingri, which is 70 km NW of Mount Everest (Qomolangma). Yadong is about a further 70 km SE of Gamba (Fig. 1b). The Paleogene sequence in these areas broadly consists of three parts: marine sandstone with intercalations of sandy limestone, massive limestone beds, gray and reddish siltstone and shale intercalated with sandy limestone (Wan et al., 2014). The Paleogene sediments overlie thick massive Cretaceous limestone unconformably, and the tops of all sections are truncated by erosion or faulting (Wan et al., 2002a).

3. Stratigraphy

3.1. Yadong section

Yadong County is located south of Gyantse in the border zone between the Greater Himalaya and Tethyan Himalaya. A Tethyan Himalaya sequence crops out around Tüna village NE of Yadong (Fig. 1; GPS location 28°04′02″N 89°11′32″E). Xiu (2011) reported ostracod assemblages from the uppermost non-caracean part of this section. The Cretaceous to Paleogene lithological succession correlates well with those described from Gamba and Tingri by Willems (1993). In this study, we stratigraphically logged the non-carbonate Yadong section and correlate it with the Eocene non-caracean Zongpubei Formation (Wan et al., 2014) at Gamba and Tingri. The Yadong section also contains representatives of the youngest marine sediments of the Tethyan Himalaya known as the Zongpubei Formation at both Gamba and Tingri.

3.1.1. Lithology

The 46 m thick Yadong section (Fig. 2), dips gently toward the southwest and consists of gray and reddish mudstone intercalated with thin siltstone and sandstone layers (Fig. 3). Graded bedding and cross-lamination indicate that the section is right-way up. Quaternary fluvial cover sediments obscure both the top and bottom of the section.

3.1.2. Biostratigraphy

The Yadong section yields numerous fossils, including foraminifers, nannofossils, ostracods, radiolarians and ichthyodonts. Planktonic foraminifer and nannofossil assemblages provide biostratigraphic age constraints.

According to our present work, six samples from the Yadong section yielded identifiable foraminifers (Fig. 4), most of which are planktonic foraminifer species like Morozovelloides coronatus, Morozovelloides crassatus, Subbotina angiporoides, Subbotina gortani, Turborotalia cerroazulensis, Turborotalia cocoaensis, Chiloguembelina cubensis and small benthic foraminifers Glomospira charoides, and Fissurina margirina. We use youngest species co-occurrences to correlate with the sub-tropical zonation of planktonic foraminifers (Pearson et al., 2006). Results show that species like C. cubensis, and Chiloguembelina ototara, occur in most samples. These taxa first appear at least in E9 zone. Taxa such as Turborotalia cocoaensis, found in the uppermost two samples, first appear in E13 zone (Fig. 5). The planktonic foraminifer species range zones constrain the Yadong section to E10–E13 covering the Middle Eocene Bartonian Stage (38–41.3 Ma).

Nannofossil results relate to a B.Sc. Honors research project by a University of Sydney student (Harvey, 2012). Most of the nannofossil species present here have long ranges. However, in the uppermost two samples, Sphenolithus obtusus, which has short range upper Lutetian to lower Priabonian (NP16 to NP18) range (Martini, 1971), is present. Therefore, deposition of the uppermost portion of the Yadong section can at least be correlated to the NP16 zone (upper Lutetian), corresponding with the foraminiferal result. Other reports include those of ostracod assemblages, which constrain the top of the formation to the lower Priabonian (Xiu, 2011).

Among the recovered taxa, reworked fossils such as Cretaceous radiolarians, the lower Eocene foraminifer Morozovella sp. and Cretaceous nannofossil species like Micula murus, Loxolithus armilla, Manivitella pemmatoidea are also observed. As reported from Gamba and Tingri, reworking of fossils in the Zongpubei Formation is common. This is cited by some researchers to question the biostratigraphic results and the marine origin of the Zongpubei Formation (Zhu et al., 2005; Hu et al., 2012). However, it has been demonstrated that reworking is very common as a result of marine circulation (Moore et al., 2012). Reworked fossils from Zongpubei Formation present a record of submarine erosion and transportation from surrounding seamounts or topographically higher regions within the sedimentary basin into the depressed Gamba–Tingri area. Alternatively, they may represent the effects of upwelling movement or circulation of the water mass in this region, rather than representing products of any terrestrial fluvial environment (Takahashi, 1990). Reworking notwithstanding, the youngest fossils identified in the Zongpubei Formation in this and former studies are marine and as such can unequivocally be used to constrain the maximum age of the final marine sedimentation. Based on these fossil records, the age of the Zongpubei Formation of Yadong can be constrained to the Bartonian to early Priabonian.

3.2. Gamba (Zongpui) section

The Zongpu section (GPS location 28°16′57″N 88°31′46″E) is located about 1 km east of Gamba County. As it is a typical shelf deposit section in the Tethyan Himalaya, many researchers have studied this section before. However, biostratigraphic constraints for this section, mainly based on the larger benthic foraminiferal faunal changes, are still the subject of discussion, especially for the Zhepure Formation (Wan, 1987; Willems, 1993; Wan et al., 2002b; Li and Wan, 2003; Wan et al., 2010; Zhang et al., 2013). In this study, we reassess the biostratigraphic results from earlier investigations of this section.

3.2.1. Lithology

Gamba (Zongpu) section is around 600 m thick and contains four formations ranging from Paleocene to Eocene (Fig. 6). The Jidula Formation (~180 m thick) is dominated by yellowish white, indurated, homogeneous sandstone, with sandy limestone intercalations in the middle and upper part. The overlying Zongpu Formation (~140 m) consists of massive limestone (dolomitized in the lower section), nodular limestone and minor amounts of calcareous marlstone and marl. The Zhepure Formation (~80 m) is composed of gray, massive and thickly bedded Alveolina packstone, with limestone beds separated by shaley intercalations. The Zongpubei Formation (~180 m) at the top of the section is gray and reddish shale intercalated with thin-bedded sandy limestone.

3.2.2. Biostratigraphy

The Zongpu section yields larger and small benthic foraminifers, planktonic foraminifers as well as ostracods. The larger benthic foraminifers, that dominate the fauna, are mainly preserved in the massive limestone of Zongpu and Zhepure formations and the limestone intercalations of the Jidula and Zongpubei formations. The larger foraminifer assemblages in the Zongpu section include Rotalia–Lockhartia and Miscellaneous–Daviarina–Operculina assemblages of the Jidula and Zongpubei formations. The larger foraminifer assemblages in the Zongpu section include Rotalia–Lockhartia and Miscellaneous–Daviarina–Operculina assemblages of the Jidula and Zongpubei formations, and Alveolina–Orientalites assemblages of Zhepure Formation (Wan et al., 2010). The P/E (Paleocene to Eocene) boundary, which marks the base of the Zhepure Formation, has been identified by
the turnover of larger foraminifer assemblages and a Carbonate Isotopic Excursion (CIE) (Wan et al., 2010; Zhang et al., 2013). Zhang et al. (2013) reported an SBZ 7 (Serra-Kiel et al., 1998) foraminifer assemblage from the Zhepure Limestone at Gamba and SBZ 6–10 from Tingri. This contrasts with the reported Early to Middle Eocene age of Wan (1987, 1990) and Willems (1993) and Willems et al. (1996). We reassess the species reported by these authors from the Zhepure Limestone, and suggest that some taxa like Nummulites laevigatus, and Nummulites obesus, identified by both Wan and Willems, are common in Tethyan region and appear after the Ypresian in SBZ 13 (Serra-Kiel et al., 1998) (Fig. 7). Other species, identified in both Gamba and Tingri regions, such as Nummulites globulus, Nummulites pengaroensis, Assilina granulose, Assilina spinosa, Assilina subspinosa, Assilina sublaminosa, Discocyclina sowerbyi, are widespread in upper Lower to Middle Eocene strata of the Himalayan region (Singh and Pratap, 1983; Tripathi and Manguin, 1986). Therefore, we suggest the Zhepure Formation in the Gamba–Tingri region ranges from the Ypresian to Lutetian.

Li and Wan (2003) reported a planktonic foraminifer assemblage from the Morozovella spinulosa–Acarinina bullbrooki zone for the

Fig. 2. Photographs from study sections in southern Tibet. (a) Yadong section. (b) Gamba (Zongpu) section. (c) Tingri (Qumiba) section.
Fig. 3. Lithostratigraphic log of Yadong section with sample distribution and foraminiferal age range. Sub-tropical zone is based on Berggren and Pearson (2005).

<table>
<thead>
<tr>
<th>Period</th>
<th>Epoch</th>
<th>Age</th>
<th>Formation</th>
<th>Sub-tropical Zone</th>
<th>Lithology</th>
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<td>Siliciclastics</td>
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<td>Calcareous Siliciclastics</td>
<td>T. cerroazulensis, G. eovariabilis</td>
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<td></td>
<td>Nannofossil</td>
<td>C. ototara</td>
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<td>Foraminifer</td>
<td>S. crociapertura</td>
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Zongpubei Formation. For this research, we re-analyzed the species occurring in the M. spinulosa–A. bullbrooki range zone of Li and Wan (2003) and other planktonic taxa of Xu et al. (1990). The faunal assemblage present indicates that deposition of the Zongpubei Formation could not have occurred before the late Lutetian (~44.5 Ma), and corresponds with our results from the Yadong section.

Fig. 5. Biostratigraphic range chart for fossils occurring in the Yadong section. Nannofossil zonation is based on Martini (1971), sub-tropical planktonic foraminiferal zone is based on Berggren and Pearson (2005). Sample distribution is illustrated on Fig. 3.

Fig. 6. Correlation of stratigraphic logs of Paleocene to Eocene strata in Gamba and Tingri areas. Stratigraphy is mainly adapted from Willems et al. (1996) and Wan et al. (2002a,b, 2014). Fossil assemblages are as reported by Wan (1987, 1990, 1991), Willems et al. (1996) and Wang et al. (2002).
3.3. Tingri (Qumiba) section

The Cretaceous to Paleogene stratigraphy of the Tingri area is well exposed in the Zhepure Mountain area, west of Tingri (GPS location 28°41′N 86°43′E). Various researchers have measured different section traverses using their own stratigraphic subdivisions in this area, especially for the uppermost non-calcareous beds (Xu et al., 1990; Li et al., 2000; Zhu et al., 2005). According to Wang et al. (2014) and observations of the authors for this study, the stratigraphic units of Tingri can be correlated with those of Gamba. Therefore, in this research, we will follow the same classification (Wan et al., 2014) for both the Gamba and Tingri areas.

3.3.1. Lithology

There is little facies variation between Gamba and Tingri. At Tingri, the Jidula Formation also consists of a group of sandy beds but with different thicknesses. The Zongpu Formation is correlated with member I–IV of the Zhepure Shan Formation (Willems et al., 1996), and consists of massive limestone that is dolomitized in the lower part. The main difference is that nodular limestone does not occur until the upper part of the Zongpu Formation (member IV of the Zhepure Shan Formation), whereas at Gamba the nodular limestone occurs at the bottom of Zongpu Formation. The Zhepure Formation is a massive limestone with abundant macroscopic Nummulites and Alveolina. The Zongpubei Formation at Tingri is correlated with the Pengqu Formation of Li et al. (2000), and is also characterized by gray and reddish shale, sandstone and siltstone. As there is a distinct color difference between the lower and upper part of the Zongpubei Formation, many researchers subdivide the Zongpubei Formation into two members, such as the Enba and Zhaguo members (Wang et al., 2002) reported a NP15 to NP20 nannofossil assemblage from the Zongpubei Formation, which constrains the timing of deposition to the late Priabonian (34.5 Ma). However, reworking is common in most microfossil studies like C. cubensis also occur at Tingri as well as in Yadong. The presence of the reworked fossils is noted not only at Tingri but also at Gamba and Yadong. However reworking is common in most microfossil studies especially for nannofossils from silty-clay particles (Ferreira et al., 2008) and we certainly do not regard all of our fossils as reworked. Therefore, together with our results from the Yadong section and the age of the underlying Zhepure Formation, we suggest that the Zongpubei Formation at Tingri and recovered both nannofossils and planktonic foraminifers. Bartonian planktonic foraminifer species such as A. bullbrooki also occur at Tingri as well as in Yadong. The presence of the reworked fossils is noted not only at Tingri but also at Gamba and Yadong. However reworking is common in most microfossil studies such as gastropods and bivalves. In this study, we sampled the top of the Zongpubei Formation at Tingri and recovered both nannofossils and planktonic foraminifers. Bartonian planktonic foraminifer species such as C. cubensis also occur at Tingri as well as in Yadong. The presence of the reworked fossils is noted not only at Tingri but also at Gamba and Yadong. However reworking is common in most microfossil studies especially for nannofossils from silty-clay particles (Ferreira et al., 2008) and we certainly do not regard all of our fossils as reworked. Therefore, together with our results from the Yadong section and the age of the underlying Zhepure Formation, we suggest that the Zongpubei Formation in the Gamba–Tingri area is of Bartonian to Priabonian age. Importantly, whether reworked or not, if Priabonian nannofossils are the youngest constituent species to those in Gamba, Wang et al. (2002) reported a NP15 to NP20 nannofossil assemblage from the Zongpubei Formation, which constrains the timing of deposition to the late Priabonian (34.5 Ma). However reworking is common in most microfossil studies especially for nannofossils from silty-clay particles (Ferreira et al., 2008) and we certainly do not regard all of our fossils as reworked. Therefore, together with our results from the Yadong section and the age of the underlying Zhepure Formation, we suggest that the Zongpubei Formation in the Gamba–Tingri area is of Bartonian to Priabonian age. Importantly, whether reworked or not, if Priabonian nannofossils are the youngest marine fossils from this area they indicate marine conditions at that time.

4. Regional correlations

4.1. Tethyan Himalaya

In the Tethyan Himalaya, the final marine stratigraphic succession is also well studied in the Zanskar region (Searle et al., 1988). Lutetian
marine deposition continued after the accumulation of nummulitic limestones. We suggest that this particular lithostratigraphic unit (Choktsi Formation) was deposited in a forearc basin setting along the southern margin of Eurasia given that it is dominated by continental margin arc-derived volcanic detritus and devoid of any ophiolitic or Indian plate derived material.

The larger foraminifer assemblages in the Kong Formation and the nummulitic limestone are dominated by species of *Nummulites*, *Assilina*, *Alveolina*, *Daviesina*, and *Lockhartia*, which is similar to the composition of assemblages from the Zhepure Formation in the Gamba–Tingri area. Previous work indicates that more than 15% of species within the Zhepure Formation are the same as those in the Gamba–Tingri region (Wan, 1987, 1990; Willems et al., 1996; Mathur et al., 2009).

4.2. Lesser Himalaya

In the Lesser Himalaya, Oligocene to Miocene continental sediments overlie Middle Eocene marine strata above a major regional unconformity, indicating a significant hiatus, which marks the change from marine conditions in the Himalayan foreland (Najman et al., 2004). Balakot is a frontier area on the northern Indian margin in the Kashmir syntaxis. The Balakot Formation consists of terrestrial sediments and is assigned to the late Priabonian (<35 Ma) (Najman et al., 2001, 2002). It unconformably overlies the marine Patala Formation of Late Paleocene to Early Eocene age (Bossart and Ottiger, 1989). The Patala Formation is dominated by larger foraminifers, and contain SBZ 4–5 assemblages (Hanif et al., 2013). The dominant species like *Miscellanea miscella*, *Lockhartia conditi*, *Lockhartia tipperi* and *Lockhartia haimei* within the Patala limestone are the same as species that dominate assemblages of the Zongpu Formation in the Gamba–Tingri region (Wan, 1991; Hanif et al., 2013). The different age of the last marine deposits beneath the unconformity in the Zanskar and Kashmir syntaxis areas, even the Tibetan region, denotes a different level of erosion in those regions. The same stratigraphic relationship also occurs in most areas west of the Kashmir syntaxis.

Southeast of the Kashmir syntaxis, the Simla basin has been regarded as an excellent location for investigations of the final marine
deposits (Bera et al., 2008). The Subathu Formation dated at 44 Ma (Bhatia and Bhargava, 2006), can be correlated with the Bhainskati Formation of central Nepal. It represents the youngest preserved marine sediments in the Himalaya foreland basin, and is unconformably overlain by alluvial sediments of the Dachshai and Kasauli formations (dated at 31 Ma) (Najman et al., 2004; Najman, 2006; Bera et al., 2008). Unlike the massive limestones of the Kohat and Patala formations, the Subathu Formation consists of variegated shales, bioclastic limestone intercalations and fine grained sandstone beds (Singh, 1978). The base of the Subathu Formation is marked by the Assilina spira abrardi bed (2–3 m thick packstone with large sized Assilines, and Nummulites) of SBZ 13. Along with the Assilina exponens-Assilina papillata-Nummulites discorbinus assemblage, the upper limit of the Subathu Formation is assigned a 44 Ma age (Mathur, 1978; Bhatia and Bhargava, 2006). In addition, Bera et al. (2008) proposed that the upper limit of the Subathu Formation must be significantly younger than 44 Ma based on reworked fossils within it. White sandstone (31 Ma) of the basal Dagshai Formation is interpreted to represent the change from marine to continental conditions.

The foraminiferal faunal composition within Subathu Formation is similar to the Zhepure Formation. More than 30% of species from the Subathu Formation are also found in the Zhepure Formation (Mathur, 1978; Bhatia and Bhargava, 2006). Notably a ~10 my erosional hiatus (41–31 Ma) exists between Subathu and Dagshai formations and the base of the latter marks the oldest non-marine sediments (Singh, 2013).

In the eastern Himalayan syntaxis, collision-related final marine sediments are also preserved in the Siang window, NE of the Assam Basin (Achariya, 2007; Achariya and Saha, 2008). The Eocene marine strata in this region are not a continuous sequence. Tripathi et al. (1978, 1981) reported an Early Eocene limestone bed in the Rengging Formation, outcropping along the banks of the Siang River, intercalated between the Miocene clastics and overthrusted by the Abor volcanics. The Rengging Formation contains abundant Nummulites assemblages including N. globulus, and Nummulites atacicus. More than 60% of the fauna is the same as those that are present in the Gamba–Tingri region (e.g. M. miscella, Globorotalia sp., L. haimei, L. conditi). The late Early Eocene to Middle Eocene Yinkong Formation, sandwiched between the Abor volcanics (Ali et al., 2012) and the Miocene Dafila Formation, outcrops in the Yamne Valley, north of the Rengging Formation (Singh and Pratap, 1983; Tripathi and Mamgain, 1986; Tripathi et al., 1988; Achariya, 1994). This unit contains thick beds of greenish gray calcareous fossiliferous shales interbedded with dark gray limestones. The limestone beds and shales yield rich Nummulites and Assilina assemblages, which can also be found in other Eocene strata that are widespread in the Himalaya (Singh and Pratap, 1983; Achariya, 2007) (Fig. 9). These striking similarities provide convincing evidence for correlation of the Gamba–Tingri–Yadong sections with other sections in the Tethyan and Lesser Himalayas as described above and the existence of a Tethyan seaway across the Lesser Himalaya.

4.3. Sub-Himalaya and Bengal basin

Other Tethyan marine deposits are also well preserved in the Sub-Himalaya zone and even in the Bengal basin, far from the IYTSZ. In the Kohat area of the western part of the Sub-Himalaya, Miocene fluvial shale, sandstone and conglomerate of the Murree Formation overlie the Mid-Eocene Kohat Formation. The Kohat Formation consists of shale and limestone in the lower part, and Nummulites limestone and Alveolina limestone in the middle and upper part, respectively (Pivnik and Wells, 1996). The Nummulites, Assilina and Alveolina assemblages

Fig. 9. Dominant species occurring in the Zhepure Formation and other correlative strata in the Himalayan regions. Fossils are reported by Afzal et al. (2009), Mathur et al. (2009), Mirza et al. (2005), Samanta (1968), Singh and Pratap (1983), Tripathi et al. (1988), Tripathi and Mamgain (1986), Wan (1987, 1990), Willems (1993), Willems et al. (1996).
within the Kohat limestone are of SBZ 14–16 ages, and they can be correlated with those of the Zhepur Formation in the Gamba–Tingri region with more than 50% of species in common for both formations (Mirza et al., 2005; Afzal et al., 2009).

In the Garo Hill region of the Bengal Basin (Jauhari et al., 2006), SE of the Siang window, the collision-related final marine sediments include the Lower Paleocene to Middle Eocene Sylhet (or Siju) Limestone Group and overlying Upper Eocene Kopili (shale) Formation. These units are succeeded by the Barail Formation (Samanta, 1965, 1968, 1969; Singh and Pratap, 1983; Alam et al., 2003; Lokho and Tewari, 2011). The Sylhet Limestone Group yields Nummulitines, Assilina and Discocyclina assemblages, which indicate shallow marine deposition similar to that in the lesser Himalaya region. The Kopili Formation consists of shale and marl, with abundant foraminifers and molluscs in the lower part and is poorly fossiliferous in the upper part, indicating a change from shallow marine to deltaic sedimentation (Samanta, 1968; Alam et al., 2008). Some species from the Sylhet Limestone also appear in the upper part of the Zhepur Formation. The facies change from limestone to shale and marl in the Garo Hill sequence is correlated with the limestone to shale sequence in the Gamba–Tingri region. The planktonic and larger foraminiferal record in the Kopili Formation indicates an upper Eocene age (Samanta, 1969), which is consistent with the age from the Zongpubei Formation.

5. Discussion

During the Early to Middle Eocene, marine shelf deposition was widespread in the Himalayan region, indicating the existence of a Tethyan seaway along the strike of the present day YTSZ, extending from Kohat, Zanskar and Simla to southern Tibet and as far as the eastern syntaxis area (Singh and Pratap, 1983). According to correlation of the larger foraminifer assemblages within these final marine sediments, we suggest that the faunas were similar and probably shared the same habitat during the pre-collision period. This seaway may even have been connected with the Bengal Basin and extended as far as the Indo–Burman suture zone. Shallow marine conditions did not change until at least the end of the Lutetian in most parts of the Himalaya region. This indicates that those regions were not close enough to the trench to undergo any subsidence (Rowley, 1998), and collision-related uplift did not occur at that time. As subduction continued, the Indian and Eurasian continental masses finally collided with each other and the Tethyan seaway disappeared as a result of syn-collisional uplift. According to our results from investigation of the last marine deposit in the Gamba–Tingri region, a Tethyan seaway still existed into the Priabonian (~38–34 Ma).

Among the stratigraphic data, the age of the youngest preserved marine deposit in the Himalaya region varies from west to east. Rowley (1996) proposed a diachronous collision to explain the differentiation between western and eastern Himalaya. However, Najman et al. (2001, 2002) questioned this in dating the Balakot Formation to no older than 36–40 Ma and suggested re-evaluation of the older age for the collision in western Himalaya was necessary. Our results show a markedly younger age for the change from marine to continental deposition in the Eastern Himalaya compared with the Western Himalaya, especially the Zanskar region. However, we note that the ages of the youngest marine strata underlying any unconformity or at the top of structurally truncated sections remain a maximum age estimates and the apparent different in maximum ages may in fact be due to a different level of erosion instead of the diachronous collision. We also note recent work that suggests the northern margin of Greater Indian was not necessarily relatively linear nor was it a simple continent-ocean boundary (Ali and Aitchison, 2014). The Bartonian to Priabonian Zongpubei Formation indicates that closure of the Tethys seaway in the Eastern Himalaya occurred after Priabonian, which is compatible with the inference of a younger collision age suggested by Aitchison et al. (2007) in this region. This result is also compatible with the Early Miocene depositional age of the first influx of Indian margin clastics onto the Lhasa Terrane (Aitchison et al., 2002), the late onset of the Higher Himalaya erosive clastics influx to the Himalayan foreland basin (Ravikant et al., 2011), the significant disgorge of detritus transported from the Himalaya to the Bengal basin by Neogene time (Johnson and Alam, 1991), and the earliest terrestrial sedimentation in the Lesser Himalaya during the Oligocene (Srivastava et al., 2013).

Although the youngest marine strata in Tibet are widely regarding as a key to placing a maximum age limit on the onset of continental collision (Rowley, 1996; Searle et al., 1988, pg. 117) this may, in fact be misleading. We note the following observations from modern collision settings such as Taiwan/mainland China (Huang et al., 2005, 2006; Byrne et al., 2011) and Timor/northern Australia (Harris et al., 2009; Harris, 2011; Haig, 2012) where collision, defined by continental crust having entered the subduction zone (beneath a colliding island arc) has begun. In both these systems a shallow marine seaway (Taiwan Strait and Timor Sea respectively) still exists somewhat inboard of the collision zone and is associated with flexural loading of the continent. On the basis of available evidence we cannot exclude the possibility that an analogous paleogeography may also have existed in southern Tibet. Given the rate of plate convergence between India and Asia the existence of any marine seaway south of the immediate zone of collision may have been short-lived and any flexural depression may have rapidly migrated southwards. If so this should be reflected in the sedimentary record. Importantly, we also note that at the same time collision has given rise to substantial relief associated with the development of significant orogenic mountain ranges. A considerable volume of sediment is being mass-wasted off this growing relief and if a similar scenario existed in Tibet we would predict the existence of synorogenic conglomerates.

6. Conclusions

Through biostratigraphic analysis of the Yadong section and reassessment of the Gamba and Tingri Paleocene to Eocene sequence, the final marine deposit in Gamba–Tingri region is assigned a Bartonian to Priabonian age. Importantly, as all sections are truncated by erosion or faulting we note that this remains a maximum estimate for the age of the last marine sedimentation in this area. By regional correlation throughout the Tethyan and Lesser Himalaya, the existence of a widespread shallow marine seaway can be reconstructed for the Middle Eocene. This Tethyan seaway ranged from western to eastern Himalayan syntaxes and may have begun to disappear at different times from west to east. As the disappearance of Neotethys is closely related to the India–Eurasia collision, and the uppermost marine deposits are regarded as an important criterion to constrain the timing of the collision, we infer that collision occurred in the eastern Himalaya during or shortly after deposition of the Zongpubei Formation in the Gamba–Tingri region.

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