Revision of the Cretaceous–Paleogene stratigraphic framework, facies architecture and provenance of the Xigaze forearc basin along the Yarlung Zangbo suture zone

Chengshan Wang a,*, Xianghui Li b, Zhifei Liu c, Yalin Li a, Luba Jansa d, Jingen Dai a, Yushuai Wei a

a State Key Laboratory of Biogeology and Environmental Geology, Research Center of Qinghai–Tibet Plateau Geology, China University of Geoscience (Beijing), Beijing 100083, China
b State Key Laboratory of Mineral Deposit Research, School of Earth Sciences and Engineering, Nanjing University, Nanjing 210093, China
c State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China
d Department of Earth Sciences, Dalhousie University, Halifax, and Geologic Survey of Canada-Atlantic, Dartmouth, N.S., Canada

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Abstract

New field investigation, structural analysis, review of biostratigraphy, stratigraphic framework, facies architecture, provenance, and flow direction of the Cretaceous–Paleogene sedimentary strata in southern Tibet resulted in reinterpretation of the evolution of the Xigaze forearc basin (XFB). The XFB is comprised by flysch-dominant Xigaze Group (consisting of Ngamring, Chongdoi, and Sangzugang Formations) and of the shallow marine Cuojiangding Group (Padana, Qubeiya, Quxia, and Gyalaze Formations), with their ages here-in revised as the Albain–Coniacian and the Santonian–Ypresian respectively. The deep-sea flysch represented by the Ngamring Formation constitutes the early sedimentary fill of the XFB. It was subdivided into five megasequences MS1–MS5 in order: the early submarine fan facies stage, channel submarine fan stage, the mature submarine fan stage, the highstand submarine fan stage, and outer fan-pelagic stage. The palaeocurrent flows were eastwards and westwards during the early and late stages of basin development and northwards and southwards during its middle stage, indicating typical forearc basin sedimentation with longitudinal supply and lateral filling. Provenance studies point to multiple sources, with andesitic debris sourced from the Jurassic–Lower Cretaceous Yeba Formation and Sangri Group formed in the volcanic island arc chains in the southern Gangdese. The four periods of the XFB development are: 1) the formation of the XFB basement by the Xigaze ophiolite, and completed before the Aptian. The coeval deposits on the shelf are the Sangzugang Formation carbonate; 2) the earliest XFB deposits of the earliest Aptian age (ca. 125/120 Ma) represented by the Chongdoi Formation, related to the residual forearc; 3) composite forearc developed, represented by the late Albian–late Cenomanian flysch megasequences (MS1–MS2) and the Turonian–Coniacian flysch megasequences (MS3–MS5), respectively; and 4) the final stage of the XFB development started the terminal forearc stage represented by the late Late Cretaceous–Early Paleogene shallow marine Cuojiangding Group and terminated during middle Ypresian, when the Gyalaze Formation was deposited.

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1. Introduction

Extensive studies were carried out in the Yarlung Zangbo suture zone (YZSZ) (e.g. Allègre et al., 1984; Gao and Tang, 1984; Coulon et al., 1986; Gao, 1988; Dewey et al., 1990; Yu and Wang, 1990; Yin et al., 1994; Yin and Harrison, 2000; Liu et al., 2010; Dai et al., 2011b; etc.). However, only few were concerned with the XFB, and only few hypotheses on its evolution have been published (e.g. Dürr, 1993, 1996; Einsele et al., 1994; Wang et al., 1999), despite that the sedimentary strata appear to be well preserved and subaerially exposed. As part of the Yarlung-Zangbo subduction zone complex, the sediments of XFB document the late subduction processes of the Neo-Tethys Ocean crust and the forearc basin development.

The biostratigraphy of XFB sedimentary strata has been established during the 1970s–1980s (Wen, 1974; Gao, 1981; Wu, 1984; Liu et al., 1988), and lithofacies and provenance studies have been published by Liu et al. (1993), Dürr (1993, 1996), and Einsele et al. (1994). However, some recently published biostratigraphic data (e.g. Wan et al., 1998, 2001; Li et al., 2008a,b) and present works on structure and sedimentology demonstrate that previous hypotheses on the time, thickness and sequences of the XFB sediments must be revised. Consequently, new interpretations on facies architecture and provenance will result in a reinterpretation of the XFB evolution.

To improve our understanding of the XFB development, we have conducted new geological field investigations of the Xigaze Group. Newly described stratigraphic profiles and outcrops, combined with structural analyses, were used to systematically calibrate the stratigraphy, to reinterpret sedimentary megasequence and provenance, and especially to reconstruct the sedimentary evolution of the XFB as well as its relationships to the YSZSZ on the basis of the revised stratigraphic framework.
2. Geological background

The YSZ comprises four major tectonic units (from north to south): Gangdese magmatic arc of Cretaceous–Tertiary plutonic and volcanic rocks (GMA), Xigaze forearc basin (XFB), an ophiolite belt and a Triassic–Eocene accretionary wedge (Fig. 1).

The GMA in southern Tibet, together with the Ladakh magmatic arc in the western Himalayas, comprise a large Ladakh–Gangdese magmatic belt over 2000 km along the strike (i.e. the Trans-Himalaya). The GMA consists of intrusive (including gabbronorite, diorite, tonalite, and granodiorite) and extrusive (including basalt, andesite, and rhyolite) rocks, in which the Cretaceous rocks with geochemical compositions of I-type granitoids and adakites are thought to have been generated by the northward subduction of the Neo-Tethyan oceanic floor (cf. Wen, 1974; Zhu et al., 2006, 2009a, 2011; Zhang et al., 2010). The intrusive rocks were emplaced over a long time period from the Late Triassic (ca. 205 Ma) to Miocene (ca. 10 Ma) (cf. Chung et al., 2009; Ji et al., 2009; Lee et al., 2009; Zhu et al., 2011). The extrusive rocks, represented by the volcanic exposures in the Early Jurassic Yeba Formation (cf. Zhu et al., 2008b), Late Jurassic–Early Cretaceous Sangri Group (cf. Zhu et al., 2009a), and Early Paleogene Linzizong Group (cf. Zhou et al., 2004; Mo et al., 2008), extend about 1500 km in a W–E direction in southern Tibet. The Gangdese thrust fault forms the contact between the GMA and the XFB in the eastern section (Yin and Harrison, 2000).

The ophiolite belt is composed of ultramafic rocks with gabbro cumulates, sheeted dyke complexes and pillow lava as well as radiolarian-bearing chert. Radiolarians date the chert as of the late Albian–early Cenomanian age (Marcoux et al., 1982). The bulk of radiometric data from ultrabasic and basic rocks yielded an age of 120±10 Ma (Göpel et al., 1984). It had previously been thought that the shortage of cumulates and sheeted dykes implies that the ophiolites were product of an abnormal oceanic crust resulting from the slowly spreading mid-ocean ridge (Nicolas et al., 1981; Xiao, 1984; Girardeau et al., 1985a,b). However, new evidence increasingly indicates that the ophiolites come from the supra-subduction zone (SSZ) (Bédard et al., 2006; Bédard et al., 2011; Hébert et al., 2011; Dai et al., 2011b). The Renbu–Zedang thrust fault in Xigaze is the contact between the ophiolites and the southern accretionary wedge (Yin and Harrison, 2000).

The accretionary wedge is a narrow elongate belt up to 1000 km long and 10–50 km wide. It consists of rocks derived from the ophiolitic complex represented by highly deformed and serpentinized pyroxene peridotite with developed schistosity and by tectonic mélangé (Gao and Tang, 1984; Gao, 1988). The accretionary wedge crops out at Ngamring, Geding, Bailang, and Zedang (Fig. 1) where it is characterized by olistoliths of various sizes ranging up to several kilometers, emplaced within the matrix of deformed and fragmented felsic sandstone and shale that comprises the Upper Triassic–Cretaceous Xiukang Group.

The strata of the XFB crop out along the Yarlung Zangbo in an east–west oriented belt, over 500 km long, which begins at Renbu in the east and ends at Zhongba in the west. The maximum width of the belt is 22 km. Our study area was focused on the western part of the Xigaze region (Figs. 1 and 2A), where the flysch-dominated Xigaze Group and shallow marine Cuojingdang Group are subaerially well exposed. The Cuojingdang Group overlies the Xigaze Group in the Zhongba area (Liu et al., 1988; Wan et al., 2001).

3. Methods

Three key methods were adopted in this study. The first method was review of past works. Previous data was refined and reinterpreted based on newly described data on biostratigraphy, isotopic chronology, petrology, sedimentary megasequence, paleocurrent direction, and provenance. The new results have been applied throughout most of the text for both the Xigaze Group and the Cuojingdang Group.

The second method was the field geological investigation. During field work, observations and descriptions of profiles, measurement of paleocurrents, and sampling for thin-sections and fossils (Figs. 2 and 3), were used to constrain the stratigraphy and to analyze the provenance of the Ngamring Formation. Especially, five profiles previously studied by Dürr (1993) and Einsele et al. (1994) were selected for further re-examination: Zhaxigang, Geding, Kardoi–Gyangqingze, Nadang–Deri, and Xishan–Beishan profiles (Fig. 2A). Several complementary profiles to the south and west of Xigaze were also studied (Fig. 2A). Of these, the typical profile is the Kardoi–Gyangqingze profile which presents the structure and stratigraphy of the Ngamring Formation (Fig. 2B). Traditional structures were analyzed for the profile by the deformation and faulting approach, and the results of structural reinterpretation were completed in Section 4.
The third method was the use of aerial photos at 1:75,000 scale, which in addition to tectonic features studied in the field allowed to locate and map regional distribution of lithological markers (Fig. 3) and megasequences in the Ngamring Formation. This process focused on two lithological markers: a sandstone–conglomerate marker that appears as steeply sloping, high, sharp ridges that are darkish in color, indicating the channel-fills of the submarine fan system; and a pelagic marlstone marker, which is identifiable on the images as a narrow, lighter-colored stripe. All the results of the lithological markers are shown in Fig. 3.

4. Structures of Ngamring Formation

The Ngamring Formation forms a synclinorium striking W-E (Fig. 2). It is asymmetric, with the northern flank 10–15 km wide and southern flank 6–8 km wide (Fig. 2B). This asymmetry may
have been result of difference in the thicknesses of sediments deposited in the distal and proximal part of the basin and/or by a northward overriding thrust on the southern flank, and/or by the lack of the Aptian–Albian sediments on the southern flank.

The structural deformation increases northward as shown by the profile (Fig. 2B). To the south, the folds are open, associated with smaller sliding folds striking west–east, commonly having axial cleavage evident in the weak layers. In the center of the synclinorium the folds become small-scale subordinate folds with axial cleavages, and strata are horizontal; in the north, the strata are strongly deformed with tightly-closed, imbricated folds.

All strata strike W–E as result of contraction in the N–S direction. The folds are asymmetric, with the structural style observed along the strike at both, the southern and northern flanks of the basin. The fold axial surfaces dip to the south at the northern flank, and northward at the southern flank (Fig. 2B). Pale strips on images which mark pelagic marlstones outcrop near the center of the synclinorium. Two of these identified on the southern flank and one at the northern flank belong to the same layer (Figs. 2B and 3), as documented by the foraminiferal biostratigraphy (Wan et al., 1998). Therefore, they are not two different horizon as previously indicated by Einsele et al. (1994).

A set of imbricated thrusts are located at the northern boundary of the synclinorium (Fig. 2B), where the mid-Cretaceous calcareous Sangzuguang Formation and the Tertiary terrestrial Gyabulin Formation are present in the thrust (Yin et al., 1994). At the southern boundary area, the contact of the Ngamring Formation is less clear than in the other areas, as most of the outcrop is covered by the Quaternary sediments. However, sedimentary contact of the Ngamring Formation is less clear in the thrust (Yin et al., 1994; Dürr, 1996; Wang et al., 1999); and (3) This assemblage is similar to the sequence of radiolarian chert and clastic rocks in the forearc basin of the Great Valley, western USA, which is an example of the typical forearc basin sequence.

5. Revision of stratigraphy

Verification of previously established litho-, bio-, and chronostratigraphy for the XFB is critical for basin analysis. Below we present new data that will revise previous studies re-interpret the ages and relationships of the stratigraphic units (Fig. 4). Two main lithostratigraphic associations represent the XFB fill. They are the Xigaze Group dominated by flysch of the Ngamring Formation, and the shallow marine Cuojiangding Group.

5.1. Xigaze Group

The Xigaze Group was originally defined by Wen (1974) as sedimentary flysch about 6000 m thick, unconformably overlying the Yanshanian granites with basal conglomerates of Cenomanian–Turonian age at its base. Later, the shallow marine carbonates of the Sangzuguang Formation were included into this group (Wu et al., 1977). In this paper, besides the Ngamring Formation and Sangzuguang Formation, the Chongdoi Formation is included as part of the Xigaze Group (Fig. 4).

5.1.1. Chongdoi Formation

This formation was named by Cao (1981) after Chongdoi village, about 20 km SE of Xigaze, where it is composed by two members. The lower member is ophiolite breccia interbedded with purplish-red radiolarian chert. The upper member is tuffaceous silstone interbedded with shale that ranges in thickness from 73 to 197 m (Xizang BGMR, 1993, 1997). Its basal contact is depositional upon the ophiolite (Fig. 5) and pillow lava and its upper contact is conformable with the overlying flysch of the Ngamring Formation (Fig. 5). In Naxia locality, the planktonic foraminifer Rotalipora spp. was found in the limestone at the top of the Chongdoi Formation (Wu, 1984) which indicates that it was deposited no later than Cenomanian. This age was also confirmed by radiolarian association found in the Chongdoi (Wu and Li, 1985; Wu, 1986), which together with the detrital zircon U–Pb isotope age of 116 Ma (Wu et al., 2010) from the siltstone in the upper of the Chongdoi Formation indicates that the strata are late Aptian to the early Cenomanian in age.

Previously, the Chongdoi Formation has been thought to be a part of an oceanic arc system (e.g. Cao, 1981; Xizang BGMR, 1997; Aitchison et al., 2000; Ziabrev et al., 2004). However, in this paper we have included it into the Xigaze Group instead of the oceanic crust association for three reasons: (1) The Chongdoi is conformable with the overlying flyschoid Ngamring Formation (Aitchison et al., 2000; Ziabrev et al., 2004), which we have also observed during our field investigation; (2) Limestone fragments of the Sangzuguang Formation are found in the Chongdoi, as well as in the Ngamring Formation (Einsele et al., 1994; Dürr, 1996; Wang et al., 1999); and (3) This assemblage is similar to the sequence of radiolarian chert and clastic rocks in the forearc basin of the Great Valley, western USA, which is an example of the typical forearc basin sequence.

5.1.2. Sangzuguang Formation

The name of this formation is after the village of Sangzuguang, Sajia County, east of Xigaze, where it crops out as tectonic fragments. It consists of dark gray, thick-bedded bioclastic limestones with abundant foraminifera and rudists, indicating shallow carbonate platform facies. The unit is 60–230 m thick (Wu et al., 1977), and decreasing to a few meters thickness about 10 km east of Xigaze, and disappears farther east at Dazhuka. It has fault contacts with either the Ngamring Formation or the Gyabulin Formation. The Sangzuguang is of Aptian–Albian age (cherchi and Schroeder, 1980; Bassoulet et al., 1984).

5.1.3. Ngamring Formation

The name was used by Wu et al. (1977) to describe Cretaceous deep-sea flysch in Ngamring County. Later it was redefined as the Cretaceous deep-sea flysch occurring above the carbonate Sangzuguang Formation (Yin et al., 1988b; Xizang BGMR, 1993, 1997). The Ngamring Formation is composed by sandstone and shale, and is characterized by a series of large channelized conglomerates in the lower part. It is conformable with the underlying Chongdoi Formation (Fig. 5) as well as the overlying Padana Formation, west of Ngamring County (Fig. 6). But it has fault contact with the Xigaze ophiolite in the south and with the Gyabulin Formation or Sangzuguang Formation in the north (Fig. 2A). However, the stratigraphic sequence, thickness and dating of the Ngamring has been misinterpreted, mainly due to the strongly deformed strata and the scarcity of fossils. Below they are calibrated on the combination of the recently published biota and age maximum of detrital zircon U–Pb isotope plus the present observation and structural interpretation in Section 4.

It is generally accepted that the structural analyses shows that rocks of the Ngamring Formation become progressively older from the synclinorium axis towards the southern and northern flanks. However, there are problems associated with the interpretation of stratigraphic sequence and thicknesses. From the axial center of the basin towards the north, the Ngamring Formation was dated as of the late Turonian age (samples 46-1, 46-2), and the middle-early Turonian (samples 47-3, XB-4, XB-5) (Fig. 3) using foraminiferal microfossils, and at eastward locations by the occurrence of ammonite Mammites sp. (Wen, 1974). Farther to the north, the rocks were dated as Cenomanian by the ammonite Turritites (T.) acutus (Wiedmann and Dürr, 1995). The Aptian–Albian age is indicated by the occurrences of larger benthic foraminifera Orbitolina (Wan et al., 1998) in the sample 14-1 (Fig. 3) and of an ammonite Neophlycticeras (T.) brottianum (Wiedmann and Dürr, 1995). On the northern boundary, the Sangzuguang Formation was dated by foraminifera as of Aptian–Albian age (cherchi and Schroeder, 1980; Bassoulet et al., 1984), indirectly indicating that the deposition of the Ngamring could not have started prior to the Aptian–Albian.
Most of the Ngamring Formation in the southern Kardoi-Gyangqingze profile (Fig. 2) are of Cenomanian age based on the foraminifera *Rotalipora cushmani* (sample 43–11) (Caron, 1985). The presence of an ammonite from *Brancoceratidae* Family found to the west of Sagoi indicates the Albian–Cenomanian age of the strata (Xiao, 1984). Foraminifera and radiolarian fossils in samples 43–16 and 43–17 (Fig. 3) indicate the early Late Cretaceous age (Yin et al., 1988b). Abundant foraminiferal assemblage (e.g. Whiteinella...

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**Fig. 4.** Diagram showing the stratigraphic framework of the XFB with data of biostratigraphy, maximum age of detrital zircon U–Pb isotopes, and lithofacies. The chronostratigraphic system is cited from Gradstein et al., 2008. The column of lithostratigraphy and lithology is composite from the review (details see in text). In the column of the biostratigraphy, the fauna of the Cuojiangding Group are quoted from Wan et al. (2001), and the biozones of the Ngamring Formation are cited from Wan et al. (1998). The column of the age maximum is cited from Wu et al., 2010.
archaeocretacea, Marginotruncana renzi, M. pilediformis) in samples 44-4 and 44-5 (Fig. 3) indicate deposition during the Cenomanian–Turonian (Wan et al., 1998). Similarly, foraminifera microfossils in samples ND-15 and ND-16 (Fig. 3), south of the Nadang–Deri profile (Fig. 2), indicate the Turonian age (Wan et al., 1998). Unfortunately, the Sangzugang Formation has not yet been observed on the southern flank of the basin, as only the Cenomanian–Turonian component of the Ngamring Formation crops out on the southern flank of the synclinorium.

The youngest strata of Ngamring Formation are of the Coniacian age and are present at the axial part of the synclinorium. The foraminiferal assemblage M. sinuosa in sample 46-2, between samples 44-5 and 47-3 (Fig. 3) indicates an age younger than the late Turonian (Wan et al., 1998). To the east, the foraminifera Dicarinella primitiva in sample XB-1 at the Xiaburi profile (Fig. 2) is an index species of the early Coniacian (Caron, 1985). D. concavata is very abundant in sample XB-3, indicating the late Coniacian age (Wan et al., 1998).

The thickness of the Ngamring Formation on the northern flank has been revised to approximately 4100 m down from 6000 to 8000 m previously estimated by Einsele et al. (1994), and it changes to 1000–4100 m thick in the region. The biostratigraphic data indicates Aptian–Coniacian age for the Ngamring Formation (Wan et al., 1998). Considering the age maxima of detrital zircon U–Pb isotopes: 107 Ma, 101 Ma, and 88 Ma from the lower, middle, and upper part of this formation (Wu et al., 2010), the age of the Ngamring Formation can be restricted to late Albian–Coniacian in age (ca. 106 to about 86 Ma).

5.2. Cuojiangding Group

The Cuojiangding Group which overlies the Ngamring flysch is included here as part of XFB sedimentary fill to provides auxiliary information about forearc basin development. The name of this Group is derived after a small lake (ca. 5400 m high) approximately 40 km north of the new Zhongba town. The group consists of the Padana Formation, Qubeiya Formation, Quxia Formation, and the Gyalaze Formation (Fig. 4), which crop out to the west of Ngamring county. It has a total thickness of 1472 m and is comprised of predominantly shallow marine sediments (Liu et al., 1988) with their age ranging from the Late Cretaceous to the Early Paleogene (Qian et al., 1982; Liu et al., 1988; Wan et al., 2001; Li et al., 2008a,b).

In previous studies the Padana Formation and Qubeiya Formation have been included in the Xigaze Group. However, both of them were deposited in a shallow marine environment (details in Section 9), therefore the depositional setting is very different from the deep-sea flysch of the Xigaze Group. In addition, they are similar to the Quxia Formation and Gyalaze Formation of the Cuojiangding Group. Therefore based on the lithofacies similarity we have changed the stratigraphic classification of the Padana and Qubeiya and included them into the Cuojiangding Group.

5.2.1. Padana Formation

The Padana Formation was named after the Padana valley southeast of Sangsang village (Liu et al., 1988). The lower part of this
formation is comprised by gray sandstone interbedded with shale and in the upper part by red shale interbedded with gray sandstone and shale. The thickness of this formation ranges from about 733 to 2000 m (Xizang BGMR, 1997). It has a conformable contact with both the underlying Ngamring Formation (Fig. 6) and the overlying Qubeiya Formation. No age diagnostic fossils were found in the Padana Formation, therefore the Santonian age suggested is an interpretation from the age of underlying Ngamring Formation and overlying the Qubeiya Formation as well as a maximum age of 88 Ma derived from detrital zircon U–Pb isotopes (Wu et al., 2010).

5.2.2. Qubeiya Formation

The Qubeiya Formation, named at the same place as the Padana Formation, is composed of yellowish-gray blocky sandy wackestone intercalated with sandstone, shale, mudstone and packstone. It is 430 m thick with the thickness increasing eastward up to ca. 1000 m in Saga County (Xizang BGMR, 1997). In the Zhongba area, it has gradational contact with underlying Padana Formation and a hiatus separates it from the overlying Gyalaze Formation. The benthic assemblages (Fig. 4) represented by foraminifera, bivalves, ammonites, gastropods, and crinoids (Qian et al., 1982; Liu et al., 1988; Wan et al., 2001), plus the maximum 78 Ma age of detrital zircon U–Pb isotope from an indeterminate stratigraphic interval in the Qubeiya (Wu et al., 2010), indicate a Campanian–Maastrichtian age of the strata.

5.2.3. Quxia Formation

The Quxia Formation, named at Quxia valley in the Cuojiangding area, is dominated by conglomerates with shale and sandstone intercalations. At the typical section the formation is 107 m thick and has paraconformable contact with underlying Qubeiya Formation and conformable contact with the overlying Gyalaze Formation (Liu et al., 1988; Wan et al., 2001). Similar to the Padana Formation, no age-diagnostic fossils have been found in the formation since it was established. Therefore, its age has been assumed to be Danian (Wan et al., 2001).

5.2.4. Gyalaze Formation

The Gyalaze Formation has been also named at Cuojiangding, where it is composed of gray and dark gray foraminiferal wackestone and packstone interbedded with sandstone and conglomerate. The thickness is over 145 m at the typical section, and the top of the formation is at the center of a syncline so its contact with the overlying unit is unclear. The age is relatively constrained better than the ages of other units of the Cuojiangding Group because foraminifera are abundant in the formation. Assemblages of the foraminiferal Miscellanea–Daviesi and Nummulites–Discocyclina (Wan et al., 2001) found in the strata indicates their late Paleocene to early Eocene (Selendidian–early Ypresian, ca. 61–51 Ma) age. Because the top of the stratum is not exposed, its age may extend to the latest Ypresian, i.e. 50–49 Ma, even younger.

6. Megasequences of Ngamring Formation

Before discussing the evolution of the XFB, we provide revision of megasequence of Ngamring Formation as it has impact on the basin filling process interpretation. Previous studies documented that the Ngamring Formation sediments were deposited in a submarine fan system (e.g. Dürr, 1993; Liu et al., 1993; Einsele et al., 1994). To better describe the submarine fan system, seven basic lithofacies terms (A, B, C, D, E, F, G) of Shanmugam and Moiola (1985) were used here. Allaby and Allaby (1999) defined a megasequence as comprised by units deposited during a distinct phase of basin evolution, separated by the major unconformities that mark changes in the basin-controlling sedimentary deposition processes. We have distinguished the megasequences of the Ngamring chiefly from lithological associations because of the difficulty in recognizing unconformities in a deep-sea basin environmental setting.

Combining structural analysis and revised stratigraphy of the Ngamring Formation, we distinguish five megasequences, termed M1 to M5 (Figs. 2B, 7, 8), in difference to the three megasequences suggested indirectly by Einsele et al. (1994). The five flyschoid megasequences we have recognized have different distributions in space, according to their proximal/distal positions in the basin (Fig. 8). For example, M5 and M3 are confined to the western area of the proximal northern flank of XFB, where lateral lithofacies lack channelized sandstone–conglomerate beds. In addition, MS3 is not easily separable from MS4 because both were deposited in a distal basin environment where sediments were much thinner than in the proximal part of the basin.

6.1. MS1, early submarine fan megasequence

MS1 occurs on both flanks of the synclinorium (Fig. 2B) and appears to be truncated by faults in the southeastern part of the XFB. On the southern flank, MS1 crops out between Kardoi and Geding where it is about 2–3 km wide and 300 m thick and is in fault contact with the ophiolites (Fig. 8) and has a sharp contact with the M5 channel conglomerate (Fig. 7). On the northern flank the megasequence is well preserved in an outcrop zone about 5 km wide, and it is in fault contact with the Gyabulin Formation and/or Sangzugang Formation. It can be subdivided into two sub-megasequences MS1a and MS1b.

6.1.1. MS1a, slope apron facies sub-megasequence

This sub-megasequence is comprised by slope facies C and D (mudstone–sandstone), intercalated with facies F (debris-flow breccias and gravelly shale), Facies C and D are comprised by alternating graded, fine-grained sandstones, siltstones and shales that define the slope. Thin black siliceous limestone also occurs as intercalations, probably formed during interruption in terrigenous supply into the basin. A characteristic feature of this sub-megasequence is the presence of facies F (debris-flow sediments).

On the northern flank, facies F was found in the profiles at Gyangqingze (sample S14) and Deri (S59). There are two debris-flow layers in the northern Gyangqingze–Kardoi profile at Gyaliek village (Fig. 2A): the first layer is debris-flow and slump sediments about 46 m thick, enclosing giant olistoliths up to 30 m × 15 m in size; the second layer, about 20 m thick, cropping out north of the thrust slice, contains some limestone gravels from the Sizanggang Formation. Also some Orbitolina fragments were found in sample S14, located about 3 km east of Gyangqinze village. The up-section profile is composed of back shale (5 m thick), deformed sandstone (7 m) and paraconglomerate (10 m). The paraconglomerate gravels
are predominantly from basic volcanics, granite and sedimentary rock. Pillow structures and chilled borders can be observed in some of the gravels.

On the southern flank, the counterpart of MS1 is the lower-middle Chongdoi Formation in Naxia. Because it is located farther from the source, the facies are lenticularly distributed gravity-flow
sandstone, forming lenses less than 20 m long and representing channelized turbidities of facies B. This facies was deposited on the northern slope of the accretionary wedge in the southern XFB. Orbitolinia fragments found on both the northern and southern flanks of the synclinorium and associated late Albian ammonite Neophlycticea spp. 7 km SSW of Gyantse village (Wiedmann and Dürr, 1995) indicate that sub-megasequence MS1 was deposited during the late Albian, probably up to the Cenomanian.

6.12. MS12, overbank facies sub-megasequence

MS12 is dominated by fine-grained, non-channelized sediments with many small-scale coarse toluft fills (facies B), and lacks the large-scale channels of MS2. This implies that there was no point-source supply from the continent during formation of MS12, which was related by Dürr (1993) to an infant submarine fan stage.

A characteristic feature of this sub-megasequence is that no coarse clasts are observed on either the southern or northern flanks. Both facies D and G occurring between Naxia and Kardoi villages on the southern flank of the synclinorium are comprised by fine-grained turbiditic sandstones and pelagic sediments, indicating a relatively stable tectonic period. A slump layer approximately 50 m thick appears in the upper part of facies D. Slumps, sandy pillow and convoluted associated with this layer suggest deposition on the lower slope. The slumped layer is overlain by a calcareous layer 34 m thick, which suggests deposition on the lower slope. The MS12 is truncated by the channel conglomerate of the MS2. Facies F is also found in the upper sub-megasequence MS12 on the southern flank (Fig. 7), differing from the MS11 in that it is not associated with channelized facies. The gravel within this facies is mostly angular and of variable composition, indicating a proximal source from the slope apron during earlier basin development. Facies F outcrops are locally found in MS12 throughout the XFB. On the northern flank, MS12 is characterized by the presence of overbank and interchannel facies, that is, by facies C and D comprising graded beddings of centimeter-thick fine-grained sandstone/siltstone and shale (Te-c or Te-f). These two facies extend laterally for up to 100 m. Locally, medium-thick (10–100 cm) coarse greywackes with suspended muddy gravels occur below facies C, which could be misinterpreted as either wide channel or channelized high-density turbidity. However, we have not yet found in the field any main channel or supply channel for sediments in the MS12. We thus interpret this facies association as overbank and interchannel facies, with the channels being small, similar to those of the Eocene Hecho Group in the Pyrenees (Mutti, 1977; in Geding by Dürr, 1996).

MS12 is dominated by fine-grained, non-channelized sediments with many small-scale coarse toluft fills (facies B) but lacking the large-scale channels of MS2. This implies that there was no point-source supply from the continent during formation of MS12, which corresponds to an infant submarine fan (Dürr, 1993).

Presence of the planktonic foraminifera R. cushmani at the top of MS12 (Wan et al., 1998) indicates a Cenomanian age for MS1 and MS2.

6.2. MS2, channelled submarine fan megasequence

MS2 is easily recognized in the field and distinguishable from the underlying MS1 in the XFB (Fig. 7), being very thick and dominated by coarse-grained terrigenous clastics. In the field it is recognizable by the strata forming high, steep relief. Five sets of channel systems at 2 to 10 km spacing were identified by mapping and remote-sensing image interpretation within a west–east oriented zone 120 km long. The MS2 in the Kardoi and Xigaze submarine fan systems is described in detail below.

6.2.1. Channel system of Xigaze submarine fan

Outcrops of the channel system of the Xigaze submarine fan are mainly present 10–20 km west and east of Xigaze town. The widest channel is about 16 km × 8 km west of the town, and about 8 km to the east. The total thickness of the channel system is about 1250 m, with a single channel fill up to 100 m thick, making it one of the largest submarine fans reported in geological history (Shanmugam and Moiola, 1985).

Five channel systems represented by sandstone–conglomerate bodies were identified in the Xigaze region: Quarry Ridge, Minor Ridge, Castle Ridge, Monastery Ridge, and West Ridge (Fig. 9A). Lithofacies in Quarry Ridge change upwards from abundant channel sandstone–conglomerate to interchannel fine-grained sediment deposited on the lower slope: channel sandstone–conglomerate, transitional fine-grained intrachannel sediment, sandstone and shale between mid-fan and lobe, to middle-out fan sediment. The Minor Ridge system comprises channel sandstone–conglomerate and interchannel sediment was deposited on the slope by episodic supply from the shelf. The Castle Ridge system appears to be a channelized sandstone–conglomerate composition overlain with an uneven surface by interchannel slope sediments (Figs. 9B, 10); the Monastery Ridge system is composed of superimposed channel fills and slope facies, and the West Ridge system consists of two channel-filled sequences.

6.2.2. Channel system of Kardoi submarine fan

A 3 km-wide channel sequence of the Kardoi Channel system exposed near Kardoi, south of the synclinorium, is the only evidence of this system deposited in a distal basin environment. They are covered by Quaternary sediments. Despite that, two sets of channel sandstone and conglomerate sequences can be distinguished as constructing the North and South Kardoi Ridges.

The South Kardoi Ridge is composed of channel facies approximately 82 m thick, displaying fining-upward and thinning-upward strata. Six superimposed channel sandstone–conglomerate bodies represent six incisions, one of which is 2 m deep. A lateral progression was observed in the first channel body present in the lower part of the channel sequence, indicating eastward migration of the channel axis. A gravel layer partly composed of boulders was found at the base of the channel system. The largest boulder is about 1.3 m in diameter, with flute casts up to 0.4 m wide and 0.15 m deep. Flute casts and the imbrication orientation of the gravel indicate deposition by a SW-flowing paleocurrent.

It has been puzzling that the sandstone and conglomerate of the South Kardoi Ridge are located within the distal basin lithofacies. Two possible explanations can be suggested: 1) the submarine fans were built directly onto the basin facies when the sea level dramatically fell below the shelf break, resulting in exposure of continental shelf; and 2) the proximal channel coarse sediments directly overlapped on the distal basin facies due to basinward migration of its depocenter. We prefer the first explanation, which implies that the basin center was located farther to the south and close to the South Kardoi Ridge.

6.3. MS3, mature submarine fan megasequence

The MS3 megasequence is present on both flanks of the synclinorium. At the southern flank it merges with the MS4 between Kardoi village and Sino-Nepal highway, where it is very difficult to separate them (Fig. 8) apart; and at the northern flank, MS3 becomes narrow, incorporating MS4 to the west of Geding village.

This megasequence is dominated by middle-out fan facies B and G, with a few occurrences of basin facies C and D. It represents an assemblage of interchannel, overbank and channel sediments similar to MS1–but, despite these similarities, the style of channel superimposition is different, indicating northward source of the sediments.

The lithofacies differ between the southern and northern flanks because of the difference in the distance from the source. In the north, MS3 facies change from retrogradation to progradation: facies B (branched channel) and facies C (lobe) grade into thinly bedded,
fine-grained turbidite-shale and medium-bedded lobe sandstone, with thinly bedded pelagic limestone at the top. In the south, MS3 consists mainly of facies C and D (outer fan-basin). Towards the top of the megasequence, sediments have a pelagic character and thinly bedded limestone occurs in the Kardoi profile.

6.4. MS4, highstand submarine fan megasequence

This megasequence is well exposed on the northern flank, but merges with the MS3 on the southern flank, partly as result of faulting.

MS4 is characterized by pelagic sediments, which can be subdivided into three sequences. The lower sequence is dominated by facies B branched channel sandstone and facies C lobe sandstone (Fig. 11). Towards the south the sediments become progressively finer, as noted in southern Xigaze (Nanshan). In the middle of MS4, the strata are grading abruptly to pelagic carbonate, showing as a pale stripe on remote-sensing images and indicating a scarcity of outer fan-basin facies C and D between the lower and middle sequence, perhaps due to eustatic sea level change. In the upper sequence, the strata are typical pelagic basin facies, that is, rhythmically interbedded black/siliceous shale, siliceous marlstone and siltstone, alternating on a centimeter scale, and enclosing few siliceous concretions. The lack of carbonates suggests
deepening of the basin, with deposition perhaps occurring below calcite compensation depth (CCD).

6.5. MS5, outer fan and basin megasequence

Megasequence MS5 occurs in the core of the synclinorium (Fig. 8), where it comprises the following three sequences:

The lowest sequence, about 240 m thick, consists of facies B and C sandstones. It can be further subdivided into three sub-sequences, the lowest of which contains many coarsening-upwards and thickening-upwards cycles, with poorly sorted mostly matrix-supported sandstones, containing muddy intraclasts. The middle sub-sequence contains beds that are fining-upwards and thinning-upwards, resulting from retrogradation and abandoned of the channels. The uppermost of the sub-sequences is composed of dark shale interbedded with facies E (thin sandstone), representing overbank or basin-outer fan sediments.

The middle sequence is about 55 m thick and is comprised by facies B sandstones. Sandstones in the channels have an erosional base, with the source being proximal to the north. In the uppermost sequence, facies C and D sandstones are intercalated with shale. The occurrence of subfacies Tc-e indicates development of an outer fan facies. Foraminifera microfossils (Wan et al., 1998) suggest Coniacian age for MS5, which thus represents the youngest deep-sea flysch deposit of the Ngamring Formation of the Xigaze Group.

7. Basement of XFB

Previous geologic studies suggested that the Xigaze ophiolite forms the basement of the XFB (e.g. Einsele et al., 1994; Wang et al., 1999). Results of new studies concur with this interpretation, but indicate that their age, nature, relation to the Neo-Tethys ocean crust, is more complex and less certain. For the convenience of discussion, the central segment of the YZSZ will here be called the Xigaze ophiolitic massif, to include the Dazhuka, Bailang, Geding, Lhaze, Ngamring, Sangsang, and Saga submassifs to the west.

In the 1980s, the Xigaze ophiolitic massif was thought to be a remnant of oceanic lithosphere formed at the spreading center (e.g. Nicolas et al., 1981; Allègre et al., 1984; Girardeau et al., 1985a,b; Girardeau and Mercier, 1988; Pearce and Deng, 1988) but later studies have indicated that the Xigaze ophiolites were formed in the supra-subduction zone (SSZ) (e.g. Aitchison et al., 2000; Wang et al., 2000; Huot et al., 2002; Hébert et al., 2003; Xia et al., 2003; Ziabrev et al., 2003; Dubois-Côté et al., 2005; Dupuis et al., 2005; Guilmette et al., 2008, 2009; Bédard et al., 2009). Recent studies note that the Xigaze ophiolitic massifs have different ages and tectonic settings.

In the Dazhuka submassif, a zircon U–Pb age of 126±1.5 Ma reported from quartz diorite (Malpas et al., 2003) is consistent with the late Barremian–late Aptian radiolarian age (Ziabrev et al., 2003). Geochemical studies of the same submassif indicate that it was formed in the supra-subduction zone (SSZ) (e.g. Aitchison et al., 2000; Wang et al., 2000; Huot et al., 2002; Hébert et al., 2003; Xia et al., 2003; Ziabrev et al., 2003; Dubois-Côté et al., 2005; Dupuis et al., 2005; Guilmette et al., 2008, 2009; Bédard et al., 2009). Recent studies note that the Xigaze ophiolitic massifs have different ages and tectonic settings.

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In the Bailang submassif, $^{40}$Ar/$^{39}$Ar dating of hornblende from three amphibolite samples yielded ages of 123.6±2.9 Ma, 127.7±2.2 Ma and 127.4±2.3 Ma (Guilmette et al., 2008, 2009), in good agreement with the zircon SHRIMP U–Pb age of the gabbro (125.6±0.8 Ma) (Li et al., 2009). Guilmette et al. (2008, 2009) interpreted these ages as indicating the initiation of intra-oceanic subduction. This conclusion is supported by geochemical studies of the ultramafic and mafic rocks that indicate the presence of a north direction Early Cretaceous intra-oceanic subduction system within the Neo-Tethyan Ocean (Huot et al., 2002).

In the Geding submassif, a gabbro yielded zircon U–Pb age of 128±2 Ma (Wang et al., 2006). This result was interpreted as the age of seafloor spreading in the Neo-Tethys. However, the mineral chemical data in contrast indicates that the Geding ophiolite was generated in an SSZ setting (Hébert et al., 2003). Geochemical studies of the Geding basaltic rocks suggest that they represent a fragment of mature mid-ocean-ridge basalt (MORB) lithosphere that has been modified in the SSZ environment (Chen and Xia, 2008).

In the Ngamring submassif, the elemental and Sr–Nb–Pb isotopic geochemical data of the mafic rocks show an affinity of N-MORB without Nb-Ta anomalies, indicating a mid-ocean-ridge or mature back-arc tectonic setting (Niu et al., 2006).

Zircon SHRIMP U–Pb dating of diabase in the Sangsang submassif shows that it was formed around 125.2±3.4 Ma (Xia et al., 2008). Geochemical studies of mafic rocks from the Saga and Sangsang submassifs indicate that they are similar to back-arc basin basalts, with small negative Nb-Ta anomalies (Bédard et al., 2009). In combination with the composition of the peridotites, Bédard et al. (2009) proposed that the mafics were formed in an intra-oceanic SSZ.

In summary, the above data show that the intra-oceanic subduction zone was located within the central segment of YZSZ during the late Early Cretaceous, which was temporally formed as the basement of the XFB. However, the western and eastern segments of YZSZ are more complex. In the eastern segment, the ages of rocks from the Loubusa and Zedang massifs range from 177 to 152 Ma (McDermid et al., 2002; Zhou et al., 2002; Zhong et al., 2006), making them older than the Xigaze ophiolites. This may explain why there was not a similar forearc basin developed over there. In the western segment, the ages of the ophiolitic rocks from Zhongba (Dai et al., 2011b), Xiugugabu (Wei et al., 2006), and Yungbwa (Li et al., 2008a,b,c; Bezard et al., 2011), show that most of them were formed around 120–130 Ma. The occurrence of the Devonian mafic rocks (Zhou, 2002; Dai et al., 2011a) that were inferred as the remnant of Paleo-Tethys indicate a much more complex geologic evolution of the ophiolites in YZSZ.

![Fig. 11. Photograph showing typical sequence of lobe facies in MS4 and MS5, 8 km SW of Xigaze town. a, shale intercalated with thin beds of fine-grained sandstone and siltstone; b, poorly sorted turbidite or rhythmic alternation of sandstone, siltstone, and shale. The circled Tibetan prayer flag on the top of the mountain is about 3 m high.](image)

![Fig. 12. Map of paleocurrent flow directions in the Ngamring Formation flysch. 1. flute cast; 2. groove cast; 3. current ripple; 4. over-banking direction; 5. pebble orientation (uni-/non-polar); 6. numbered data points: 1–48 for data based on the present study, and 49–94 for data from Dürr (1993); and 7. village and town.](image)
8. Provenances of XFB sediments

8.1. Paleocurrent pattern

Paleocurrent analysis provides important information about provenance, geometry of the depositional units, and depositional processes. During field work, paleocurrent directions were obtained at 48 localities (Table S1). Another set of 46 paleocurrent data was published by Dürr (1993). Both of these sets of data demonstrate a predominantly southward paleocurrent flow and subordinately westward and eastward directed flows (Fig. 12). This has previously been interpreted as indicating that the XFB was chiefly supplied by sediments from the GMA located to the north, and partly from the ophiolite belt to the south (e.g. Dürr, 1993, 1996). Our data supports this conclusion. For example, much of the ophiolitic detritus–basic volcanic rocks, chert, and calcite- and epidote-replaced pyroxenes from the MS1 in the south were found in the sandstones in the Naxia profile where the paleocurrent flow directions are NNE 10°. However, another group of paleocurrents in MS1 indicated an eastward flow direction (Fig. 12), and that at both the southern and northern flanks. This suggests a change in flow direction after current reached a southerly point, where it might have been obstructed by either morphological elevation on the seafloor, or by the presence of an accretionary wedge that constrained the current to flow in the axial direction of the basin. The observed eastward paleoflow supports basin asymmetry and a W–E axial direction of the XFB.

Paleocurrent flow direction was unified during MS2, when the flow was southward, with minor SW flows, indicated by flute cast and gravel imbrications in the Kardoi and Naxia area (Table S1, Fig. 12). This can be attributed to the complete infilling of the basin, causing sediment to bypass it into the trench, and therefore indirectly implying that the basin subsidence center had migrated farther to the south.

After MS2 deposition, both eastward and westward paleocurrent flow are found in MS3–MS5, as well as the southward and northward flow. The highly variable paleocurrent flow directions can be explained by source supplies from the south and the north superposed on westerly and easterly sources, in a similar fashion to the Great Valley forearc basin, in western USA (e.g. Ingersoll, 1979; Moxon, 1988, 1990; Williams, 1997).

8.2. Sources of andesitic component

Petrological texture, mineralogical composition and geochemistry (Fig. 13) have shown that volcanic detritus in the Ngamring Formation was mainly derived from andesites (Dürr, 1996). The shortage of rhyolitic and dacitic detritus indicates that the source of the detritus could have been remelting of originally basaltic mantle (e.g. lower crust or subducted oceanic lithosphere), but not from remelting of the middle to upper crust (Gill, 1981), which is dominated by SiO2-rich magma, as seen in northern Chile, northern Peru, and western America (Schmincke, 1986). Previous studies indicate that a thinned or transitional continental crust could have existed in the southern GMA during the Early Jurassic through the Early Cretaceous (e.g. Dong et al., 2006; Geng et al., 2006; Zhu et al., 2008a,b, 2009a,b, 2011), where andesitic volcanic rocks could have been formed (e.g. the Sangri Group andesites, Zhu et al., 2006, 2009a) and thereafter eroded.

What could be the sources of the andesitic components in the Ngamring Formation? A probable derivation is that they were sourced from older volcanic strata in the GMA, as represented by the Yeba Formation and Sangri Formation. Macrofossils (Yin et al., 1998) and isotopic chronology indicate that the Yeba Formation is early to middle Jurassic (e.g. Geng et al., 2006; Zhu et al., 2008a,b, 2009a,b) and that the Sangri Formation is late Jurassic to early Cretaceous (Dong et al., 2006; Zhu et al., 2009a). These ages match the two principal magmatic periods obtained from detrital zircon studies of the Ngamring Formation (Wu et al., 2010). The Yeba Formation is characterized by the rare occurrence of intermediate rocks (Zhu et al., 2008b) while the Sangri Group is dominated by the presence of andesites and andesitic breccias with dacites (Dong et al., 2006; Kang et al., 2009; Zhu et al., 2009a). This means that the sedimentary–volcanic sequence of the Late Jurassic–Early Cretaceous Sangri Group in the southern GMA was the primary source of andesitic material from the Ngamring Formation flysch. This conclusion is consistent with the recent recognition of Wu et al. (2010), who identified a principal magmatic period between 130 Ma and 80 Ma (peaking at around 110 Ma) and a subordiniate period between 190 Ma and 150 Ma (peaking at 160 Ma) from detrital zircons from sedimentary rocks in the XFB.

The explanation could be the presence of older volcanic strata south of the GMA, as represented by the Yeba Formation and Sangri Formation. Macrofossils (Yin et al., 1998) and isotopic chronology indicate that the Yeba Formation is early to middle Jurassic (e.g. Geng et al., 2006; Zhu et al., 2008a,b, 2009a,b) and that the Sangri Formation is late Jurassic to early Cretaceous (Dong et al., 2006). These ages match the two principal magmatic periods obtained from detrital zircon studies of the Ngamring Formation (Wu et al., 2010). The Sangri Group is dominated by andesite lava and andesitic breccia with dacites, indicating that their origin is related to arc-type volcanic rocks formed in the lower crust during the Neo-Tethys oceanic crust subduction (Dong et al., 2006; Kang et al., 2009). The above ages of the Yeba and Sangri formations strongly suggest that the two Mesozoic sedimentary–volcanic sequences in the southern GMA were the source of andesitic material for the Ngamring flysch.

The composition and geochemistry of the sediments also show that the andesitic and other volcanic lithiclastics are common in the lowest sequence of the Ngamring Formation, but their occurrence decreases upwards. A possible explanation is that as increasing amounts of terrigenous materials were transported into the XFB, older rocks were eroded as the GMA was denuded. As a result, the younger volcanic rocks were the source for the lower part of the sequence, while the upper part of the XFB strata was supplied from progressively older rocks during unroofing of GMA. This reversal is supported by recent results of detrital zircon U–Pb and Hf isotopic analyses. Most zircon ages from the lower flysch of the Ngamring Formation are
characterized by positive εHf(t) values similar to those of magmatic zircons from the Gangdese batholith and from the upper Ngamring and Padana–Qubeiya formations. The younger sequences record either pre-Mesozoic U–Pb zircon ages or negative εHf(t) values (Wu et al., 2010).

9. Discussions

9.1. Sedimentary evolution of XFB

The forearc basins develop as part of the trench–arc system above the subduction zone. Dickinson and Seely (1979) classified the forearc basins into five types: intramassif basin, residual basin, accretionary basin, constructed basin, and composite basin. Combination of the revised stratigraphic framework and of the basin basement, lithofacies architecture (megasequences), and provenance study have resulted in our recognition of four distinct stages in the XFB development: basin formation, residual forearc, composite forearc, and terminal forearc. The basin formation period is represented by the Sangzugang Formation which was deposited on a narrow shelf at an active continental margin. Residual and composite forearc basin periods are represented by the Ngamring Formation, comprising five successive megasequences of the submarine fan. The terminal forearc period is represented by the Cuojiangding Group. The change of the forearc basin type could indicate a linkage to the termination of the subduction of the New-Tethys oceanic lithosphere.

As discussed in Section 8.2, andesitic clastics are common within sediments of the XFB, indicating that partial melting of lower crust or subducted oceanic lithosphere should have been processed in its north before the XFB formation (SU1, Fig. 14A). Such melting event could be attributed to the subduction of the Neo-Tethyan oceanic lithosphere that resulted in extensive volcanism occurred in the southern margin of the Lhasa terrane (Zhu et al., 2006, 2009a,b, 2011), as represented by the Sangzi Group that could have provided andesitic materials for the XFB. By the standing subduction, an intra-oceanic system (including the northward-subducted zone, oceanic island-arc and intra-arc basin) was formed in south of the open Neo-Tethys ocean (SU2, Fig. 14A, for details refer to Hébert et al., 2011), during which the SSZ-type Xigaze ophiolites were generated. According to the ages of the Xigaze ophiolite (see in the Section 7) and XFB (see in Section 5.1), it is reasonable to conclude that the subduction may have terminated about 120 Ma ago.

In comparison to the older normal oceanic crust, the SSZ-type Xigaze ophiolite has a light density, for which it would have never been intermixed with the mantle lithosphere. Therefore, it was obducted toward the south and became the basement of the XFB in the late Early Cretaceous (SU2, Fig. 14B and C). At the same time, the Sangzugang Formation carbonates were deposited on a narrow continental shelf. During the same time, the residual forearc basin was formed by the initiation of the typical arc–trench system of the YZSZ.

The residual forearc basin represents the earliest stage of the XFB development, represented by the late Alban–mid Cenomanian Ngamring Formation flysch (MS1) and by the Chongdoi Formation. During this period, submarine fan and slope facies spread out into the basin. As described in Section 6.1, the evolution of the megasequence MS1 can be subdivided into two stages (Fig. 7): in the first stage, MS1\(^1\) is characterized by slope facies mudrock and siltstone intercalated with debris-flow breccia and gravely mudrock, dominated by non-channelized debris-flow sediment in apron facies in the north and by rare lenticular and sheet turbidite sandbodies of facies B. During the second stage, MS1\(^2\) was formed by overbank sediments, and it features non-channelized fine-grained sediment facies, during which supply channels were not incised for transportation of detritus from either the GMA or the carbonate platform on the narrow margin, indicating no point sources, despite the fact that the XFB contains sediments from both the carbonate platform in the north and from the Xigaze ophiolite and the accretionary wedge in the south.

Frequent debris of orbitolinitid-bearing limestone found in the basal Chongdoi Formation indicates that erosional clastics from the northern carbonate platform reached as far as the southern XFB. Such interpretation is supported by positive initial εHf(t) values of zircons derived from the GMA (Wu et al., 2010). The east–west paleocurrent direction (Fig. 12) indicates that the accretionary wedge formed a morphologic high on the sea floor and that the subsidence center was located south of the XFB.

During the middle-late Cenomanian, the XFB changed from a residual basin to a composite basin, and the accretionary wedge also became a part of the basement of the basin. At this time, large submarine fan channelized systems developed in the deep-sea basin (Figs. 7, 8, 9), while the carbonate platform was exposed to subaerial conditions and eroded when sea level dropped sharply. Subsequently, large amounts of sediment were brought up to the accretionary wedge, and in places channels approached the trench. This is evident by the occurrence of only two sets of channel fill sequences deposited in the distal basin setting where they directly downlapped onto pelagic limestone in the Kardoi region. During the stage, the direction of sediment supply to the basin changed from lateral to longitudinal, attributable to the tectonic barrier caused by emplacement of the accretionary wedge and trapping sediments in the XFB. This tectonic activity resulting from ocean crust subduction extended farther to the north, as evidenced by folding of the Takena Formation in the Lhasa retroarc basin (Coulon et al., 1986).

The composite forearc basin matured during the early-middle Turonian (Fig. 7) when MS3 was built by middle and outer fan facies. During this time period sediment supply decreased. On the north of the basin, the megasequence is formed by branched channel sandstone of facies B and lobe sandstone of the lower part of facies C, grading upward into fine-grained turbiditic and lobe sandstones; the top strata contain thin pelagic limestone layers, indicating a pelagic environmental setting. In the south, MS3 is dominated by facies C lobe sandstone and facies D outer fan-basin fine-grained sediments.

During the middle-late Turonian, the composite forearc basin was constructed by MS4 (Fig. 7) consisting of branching channel lobe sandstone and abundant basin facies. At the top of this megasequence, light-gray pelagic limestone provides significant late-Turonian marker for correlation between both flanks of the synclinorium. The composite forearc basin development stage weakened during the Coniacian. It is represented by MS5, which is comprised by the outer-fan and basin facies (Fig. 7).

As revised in Section 5, the change from the deep-sea facies to shallow-sea facies lies between the Ngamring Formation of the Xigaze Group and the Padana Formation of the Cuojiangding Group. That means either the age at the base of the Padana or the age at the top of the Ngamring represent the termination of the deep-sea deposition. This time would mark either the termination of the composite forearc basin or the initiation of the terminal forearc basin. The revision of stratigraphy (details refer to Section 5) shows that the Ngamring Formation is of late Alban–Coniacian age and the Padana Formation is of Santonian age, indicating that deposition in the XFB changed from deep-sea facies to shallow-sea facies at ca. 86 Ma.

The terminal sedimentary succession of the XFB is represented by the Cuojiangding Group comprised by Late Cretaceous–Early Paleogene shallow marine carbonates and terrigenous rocks that crop out west of Ngamring. This shallowing-up sequence could be attributed to the decreasing accommodation space for basin filling material (Fig. 14C). The hypothesis is supported by the conformable contact between the Xigaze Group and the Cuojiangding Group (Fig. 6).

Relatively, it is simple to date the termination of the XFB. The Gyalaze Formation at the top of the Cuojiangding Group is generally thought to be the marine sediment record of the XFB. We then
suggest that the termination of the Gyalaze Formation deposition represents the termination of XFB. As revised in Section 5.2, the Gyalaze Formation is of Selandian–Ypresian age (top age, ca. 50–49 Ma), so we propose that the XFB terminated at about 50–49 Ma.

As a whole, the sedimentary succession of the XFB represents a typical composite basin (Dickinson, 1995). The XFB developed in the forearc area with sediments extensively supplied from the continental magmatic arc. The sedimentary succession of pelagic radiolarian chert, shale and microfossil-bearing tuff in the lowest layer, flysch submarine fan facies in the middle, and coastal-shallow facies in the upper strata documents the evolution of the basin subsidence center.

9.2. Comparison between Indus Forearc Basin and XFB

In Ladakh–Indus, the suture is named the Indus Suture Zone. Considered together with the YZSZ, it was named the Indus–Yarlung Zangbo Suture Zone (Searle et al., 1997; Henderson et al., accepted for publication), and is regarded as the site of the collision between the Indian and Eurasian continents (e.g. Gansser, 1977, 1980; Shackleton, 1981; Tapponnier et al., 1981). Similar to the XFB, the Indus Forearc Basin developed in the Indus Suture Zone. Starting on the Ladakh magmatic arc in the mid-Cretaceous, development of the Indus Forearc Basin terminated in the early Eocene, as marked by an intermontane molasse (Van Haver, 1984; Garzanti and Van Haver, 1988). It is obviously instructive to compare the two.

As is evident from their present structure, both are asymmetrical, with the one exception of near-symmetry appearing in the eastern XFB. This could have resulted from thrusting in collision and/or from different thicknesses in the original deposition.

A complete terrigenous to carbonate succession 1500 m thick was deposited in the southern Indus Forearc Basin, similar to the XFB. Facies change through time show similar sequences of shallowing-upwards megasequences (turbidite to nummulitic limestone), and alluvial to deltaic sediments occur in both forearc basins.
deposition began with orbitolinid and rudist carbonates at almost the same time, shown by the Khalsi Formation in Indus and the Sangzugang Formation in Yarlung Zangbo.

Further, the terrestrial coarse successions above the forearc basin that started to develop following the early Eocene show a great deal of similarity in both regions. A set of conglomerates and sandstones 250–1600 m thick, nonconformable on the marine Gyalaze Formation limestones and sandstones of the top XFB in Cuojiangding Lake, northern Zhongba, correlate with those of the Hemis conglomerate in the Indus basin. It is interesting that the terrestrial succession was transported westward in the Indus basin, mostly fed from the northeast (Frank et al., 1977; Baud et al., 1982) and became more distal toward the west and south. It is inferred that this change represents the initiation of collision between two continents and implies an oblique collision from east to west; however, much work needs to be done in the future to test this hypothesis.

There are two distinctions between the two basins. One is that the position of shallow water carbonate deposition is different: the Khalsi Formation is located between the Indian Ophiolite Complex and Indian Forearc Basin, whereas the Sangzugang Formation is positioned on the northern margin of the XFB. The other difference is the timing of the beginning of the deep-sea flysch; the deposition of the Ngamring Formation started earlier than the late Albian in XFB, and the Tar Formation (deep-sea turbidite) began in the Maastrichtian or even in the Paleocene. This distinction is profound, and implies either diachronity or obliquity of the Neo-Tethyan oceanic crust subduction. This is also evident in the Indus Basin. Shallow-sea nummulitic limestone was deposited in the west followed by deltaic succession, with deep-sea turbidite occurring in the south-east (Garzanti and Van Haver, 1998).

10. Summaries and conclusions

The XFB resembles a typical forearc basin in its filling pattern and basement lithology (Dickinson, 1995; Dickinson and Seely, 1979). The basin has a shallowing-upwards sequence of pelagic and turbiditic deep-sea facies, from near-shore shelf through to continental facies, dated from the late Aptian through the Ypresian (ca. 120–49 Ma) with a duration of about 71 Myr. The basin is narrow (20–22 km wide in the north–south direction) and 550 km long in the east–west direction. The sedimentary fill is asymmetric. The N–S shortening ratio has been estimated as ≥31% for the Gyabulin Formation and ≥65% for the Ngamring Formation (Ratschbacher et al., 1992), which makes the dimensions of the original XFB were ≥71 km wide and 50–100 km long, thus comparable in size to a large forearc basin (Dickinson, 1995; Dickinson and Seely, 1979).

The combination of the revised stratigraphic framework, reinterpretation of lithofacies architecture, provenance, and basin basement, leads to the following conclusions:

1) The XFB consists of two main lithostratigraphic associations: the Xigaze Group and the Cuojiangding Group. The former group consists of the Sangzugang Formation, Chongdoi Formation, and Ngamring Formation, with their ages revised as the late Aptian–early Albian, middle Aptian–Albian, and middle Albian–Coniacian, respectively. The thickness of the Ngamring Formation was revised to less than 4000 m on the basis of the structural analyses of studied profiles. The Cuojiangding Group is composed of the Padana Formation, Qubeiya Formation, Quxia Formation, and Gyalaze Formation, ages of which were revised as Santonian, Campanian–Maastrichtian, Danian, and Selandian–Ypresian, respectively. Most of the formations have conformable contacts with each other except of the Sangzugang Formation, which is disconformable with others.

2) The Xigaze Group is dominated by deep-sea fan flysch lithofacies, except for the Sangzugang Formation, which is comprised by shallow carbonate platform lithofacies. The Cuojiangding Group is characterized by shallow-marine mixed terrigenous and carbonate rocks. The gradual upward transition from the deep-sea flysch facies of the Ngamring Formation into the shallow marine facies of the Padana Formation indicates progressive basin filling rather than tectonic activity, which is tentatively dated at the boundary (ca. 86 Ma) of the Santonian and Coniacian.

3) The deep-sea fan represented by the Ngamring Formation consists of sandy turbidites, channeled sandstones and conglomerates with a few thin pelagic limestone and calcareous shale. Sedimentary beds are arranged into five megasequences (MS1–MS5), comprised by the early submarine fan, channeled submarine fan, mature submarine fan, highstand submarine fan, and outer fan and pelagic sediments. MS1 has been further subdivided into the slope apron facies sub-megasequence (MS1δ) and the overbank facies sub-megasequence (MS1β). Megasequence MS2 can be subdivided into the channel system of the Xigaze submarine fan and the channel system of the Kardoi submarine fan.

4) Former data plus ours show that the paleocurrent flows were eastwards and westwards during the early and late stages of basin development and northwards and southwards during its middle stage, indicating typical forearc basin sedimentation with longitudinal supply and lateral filling. This change in directional sediment supply to the basin can be attributed to the tectonic barrier caused by emplacement of the accretionary wedge and trapping sediments in the XFB.

5) The provenance analysis supports a new interpretation that the andesitic detritus of the XFB may have been derived from the Jurassic–Early Cretaceous arc-volcanic Yeba Formation and Sangri Group south of the GMA, but not from the batholith or/and Paleogene volcanic rocks in GMA, implying that obduction of the SSXigaze ophiolite may have been directed toward the south.

6) Four distinct phases of the XFB development we recognize are the basement formation, residual forearc, composite forearc, and terminal forearc. The main basement of the XFB is formed by the Xigaze ophiolite, formed prior the Aptian (ca. 120 Ma), with the coeval counterpart on the continent being the carbonate Sangzugang Formation. The residual forearc may have initiated in the earliest Aptian (ca. 125/120 Ma), as represented by sedimentary deposits of the Chongdoi Formation. Then the residual forearc and composite forearc developed, represented by the late Albian–Coniacian flysch megasequences of the Ngamring Formation. The terminal forearc continued through the late Late Cretaceous–Early Paleogene (ca. 86–49 Ma), represented by the shallow marine Cuojiangding Group, and would have not terminated until the latest Ypresian (ca. 50–49 Ma) by the Gyalaze Formation.

7) The studies of stratigraphy, lithofacies and provenance as well as comparison to other typical forearc basins not only can contribute to the understanding of the sedimentary evolution of the XFB, but also are significant to the evolution of YZSZ. From the records of XFB, we suggest that the Neo-Tethys oceanic crust may have been subducted at two different times and obducted once.

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