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Paleocene–Eocene record of ophiolite obduction and initial India-Asia collision, south central Tibet

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[1] Uppermost Cretaceous to Eocene marine sedimentary sequences occur both to the south and north of the Yarlung Zangbo suture in south central Tibet. They consist of Indian-margin strata of the northern Tethyan Himalaya and Asian-margin strata of the Gangdese forearc. Both assemblages are characterized by major changes in depositional environment and sedimentary provenance at ~65 Ma and an appearance of detrital chromium-rich spinel of ophiolite affinity (TiO_2 generally <0.1 wt%) during the Paleocene. Ophiolitic melange exposed along the suture could have provided a source for detrital spinel. The melange occurs in the hanging wall of a north dipping, south directed mylonitic shear zone which includes a tectonic sliver of mafic schist. Amphibole from the schist yields $^{40}Ar/^{39}Ar$ ages of ~63 Ma, which we attribute to cooling during slip along the shear zone and southward obduction of the melange. Melange obduction was coeval with the development of an angular unconformity within the Gangdese forearc basin to the north (between late Maastrichtian time and ~62 Ma). Upper Paleocene to middle Eocene sandstones in the northern Tethyan Himalaya yield 200–120 Ma U-Pb detrital zircon ages and 190–170 Ma $^{40}Ar/^{39}Ar$ detrital mica ages. These detrital grains were most likely sourced from regions north of the Yarlung Zangbo suture, suggesting that onset of India-Asia collision in south central Tibet is middle Eocene or older in age. Collectively, our results support previous suggestions that oceanic rocks were obducted onto the northern margin of India during latest Cretaceous–earliest Tertiary time. Coeval changes in Gangdese forearc sedimentation raise the possibility that this obduction event marks onset of tectonic interaction between India and Asia at ~65 Ma. Alternatively, in concert with the conventional view of Eocene collision initiation, the obducted oceanic rocks may be of intraoceanic origin, while coeval changes in Gangdese forearc sedimentation may be a consequence of an increase in the rate of ocean-continent convergence following the demise of the intraoceanic subduction zone.

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1. Introduction

[2] In addition to creating the Cenozoic Himalayan-Tibetan orogenic system, the collision between India and Asia may have played a major role in altering drainage patterns of major rivers in Asia [*Brookfield*, 1998], ocean-water chemistry and currents [*Raymo et al.*, 1988; *Richter et al.*, 1992; *Stille*, 1992], and climate [*Kutzbach et al.*, 1989; *Ruddiman and Kutzbach*, 1989; *Raymo and Ruddiman*, 1992]. To fully understand these and other manifestations of India-Asia collisional orogenesis requires accurate constraints on when the collision process began. Furthermore, estimates for the magnitude of postcollisional convergence and the total volume of Indian crust which has been incorporated into the Himalayan-Tibetan orogen depend heavily on knowledge of collision time and its potential variation along strike of the Himalayan orogen [e.g., *Le Pichon et al.*, 1992; *Rowley*, 1996; *DeCelles et al.*, 2002].

[3] The initiation age of India-Asia collision is taken to represent the time of disappearance of the Neo-Tethys oceanic lithosphere and first contact between Indian and Asian continental crust. This age has been difficult to constrain as reflected by the wide range of estimates for the onset of collision (70–38 Ma), most of which are minimum estimates or are based on indirect evidence (see reviews and references from *Butler* [1995] and *Yin and Harrison* [2000]). Although specific geologic relationships are still debated, there is a general consensus that India-Asia collision initiated no later than ~55–52 Ma in the north-western Himalaya on the basis of the ages of postcollisional

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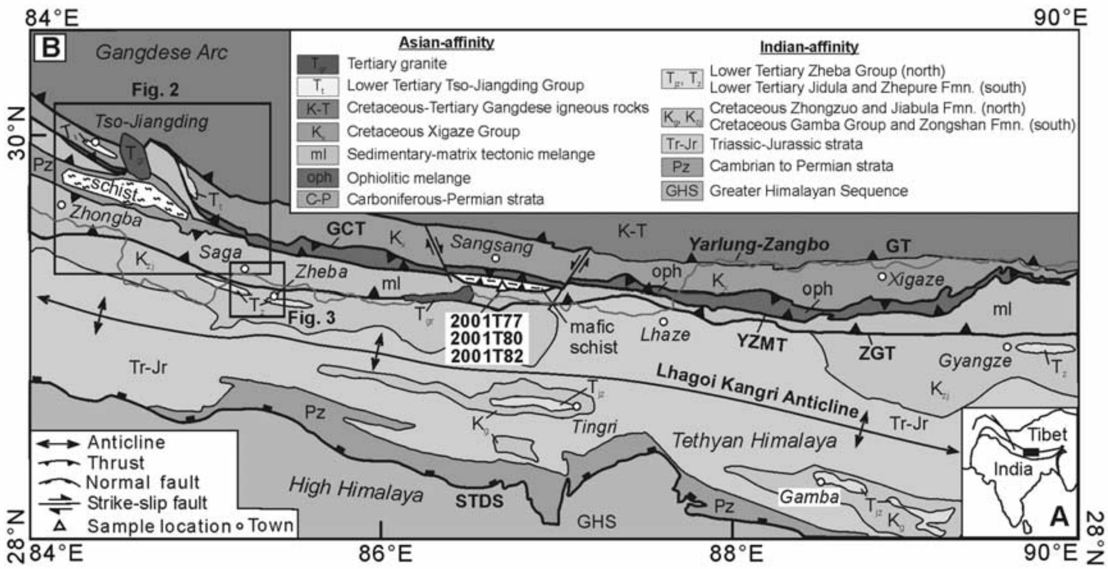

Figure 1. (a) Inset map shows location of study area in south central Tibet. (b) Simplified geologic map of south central Tibet based on *Liu* [1988] and our own observations. Additional significant fold-thrust belt structures occur within the Tethyan Himalaya but are not shown here for clarity. Abbreviations are as follows: GCT, Great Counter thrust; GT, Gangdese thrust; STDS, south Tibetan detachment system; YZMT, Yarlung Zangbo Mantle thrust; ZGT, Zhongba-Gyangze thrust. See color version of this figure at back of this issue.

stratigraphic assemblages [e.g., *Searle et al.*, 1987; *Gaetani and Garzanti*, 1991; *Beck et al.*, 1995, 1996; *Searle et al.*, 1997], high-pressure metamorphic rocks [e.g., *Tonarini et al.*, 1993; *Guillot et al.*, 1997; *de Sigoyer et al.*, 2000], and paleomagnetic studies [e.g., *Besse and Courtillot*, 1988; *Klootwijk et al.*, 1992, 1994]. A robust estimate for the maximum age of collision is provided by formation ages of the youngest ophiolitic fragments documented (70–65 Ma [*Gnos et al.*, 1997]).

[4] Relative to the northwestern Himalaya, the closure history of the Neo-Tethys Ocean in Tibet is poorly known. Changes in sedimentation patterns and the appearance of accretionary prism and arc material within Maastrichtian strata of the southern Tibetan Tethyan Himalaya have been attributed to onset of interaction between India and Asia at this time [e.g., *Liu and Einsele*, 1994; *Shi and Yin*, 1995; *Liu and Einsele*, 1996; *Willems et al.*, 1996]. However, these changes in sedimentation may be equally well explained by southward obduction of Neo-Tethys intraoceanic rocks, including ophiolitic fragments and subduction-accretion complexes, onto the northern margin of India during Late Cretaceous–early Tertiary time prior to India-Asia collision [*Allègre et al.*, 1984; *Burg and Chen*, 1984; *Burg et al.*, 1987; *Searle et al.*, 1987; *Beck et al.*, 1996; *Gnos et al.*, 1997; *Makovsky et al.*, 1999; *Aitchison et al.*, 2000]. Further questioning an early age for collision in southern Tibet is the lack of evidence for Asian-derived detritus or increased rates of tectonic subsidence in Paleocene–Eocene strata of the Tethyan Himalaya [*Rowley*, 1996, 1998; *Aitchison et al.*, 2000, 2002]. This, together with recognition of an Indian promontory in Kashmir [e.g., *Treloar and Coward*, 1991], counterclockwise rotation of India [e.g., *Patriat and Achache*, 1984; *Klootwijk et al.*, 1985; *Dewey et al.*, 1989], and the lack of evidence for Paleocene to early Eocene high-pressure metamorphism within the central and eastern Himalaya, have contributed to the popular view that collision first began in the western Himalaya and subsequently propagated eastward [e.g., *Rowley*, 1996].

[5] In this paper, we present new geologic mapping and geochronologic, thermochronologic, and stratigraphic studies of the northern Tethyan Himalaya, Yarlung Zangbo suture, and Gangdese forearc region of south central Tibet. Our results provide the first robust constraints on the timing of oceanic rock obduction and collision initiation along this part of the India-Asia suture. Two models for the latest Cretaceous–early Tertiary history of Neo-Tethys Ocean closure are presented along with their major implications and predictions.

2. Geologic Setting

[6] The study area spans the Yarlung Zangbo suture in south central Tibet (Figure 1a) and includes from south to north the following lithotectonic units: (1) Tethyan Himalaya, (2) Yarlung Zangbo suture zone, (3) Gangdese forearc, and (4) Gangdese arc. The Cretaceous–Tertiary geology of each of these units is summarized in the following.

2.1. Tethyan Himalaya

[7] Cretaceous–lower Tertiary marine sedimentary sequences in the Tethyan Himalaya were deposited on older strata of the northern Indian passive continental margin

(Figure 1). They have been divided into northern and southern units because of the presence of major intervening structures and differences in lithology [e.g., *Burg et al.*, 1987]. The southern unit is composed mainly of carbonate and clastic sedimentary rocks ~5 km thick [*Jadoul et al.*, 1998; *Wan et al.*, 2000]. In the Gamba-Tingri area (Figure 1), the youngest well-documented marine strata are Lutetian in age [*Wen*, 1987a, 1987b; *Willems et al.*, 1996; *Xu*, 2000]. The northern unit consists of sandstones, shales, and limestones [*Sheng*, 1976; *Wu*, 1987; *Yin et al.*, 1988]. Because of the scarcity of stratigraphic studies, large-fossil records, and detailed radiolarian biostratigraphic correlations, the thickness (previous estimates vary from 5–10 km) and age of the northern unit remain poorly constrained.

[8] The northern unit includes the uppermost Cretaceous Zhongzuo Formation, which consists of successions of shale, sandstone, and coarse-grained sandstone interbedded with lenses of planktonic-benthic foraminifera-bearing limestone and radiolarian chert [*Wan and Ding*, 2002]. The Zhongzuo Formation is overlain by recently discovered Paleocene–Eocene marine sequences [*Ding*, 2003] which outcrop in the Zheba area, ~50 km north of previously documented marine sequences of similar age in the southern unit near Gamba and Tingri (Figure 1) [*Wen*, 1987b; *Willems et al.*, 1996; *Rowley*, 1998; *Xu*, 2000]. Considering major Cenozoic upper crustal shortening in the Tethyan fold-thrust belt (~67% [*Ratschbacher et al.*, 1994]), the two areas may have been ~150 km apart in the north-south direction during the Paleocene.

2.2. Yarlung Zangbo Suture Zone

[9] The Yarlung Zangbo suture zone (YZSZ) marks the contact between igneous and sedimentary rocks of Asian affinity to the north from Indian continental margin strata of the Tethyan Himalaya to the south. It is characterized by a generally narrow (<15 km), approximately east-west belt of oceanic rocks which represents obducted remnants of the Neo-Tethys Ocean. In our study areas (Figure 1), these are largely restricted to ophiolitic melanges. However, in the Xigaze area to the east (Figure 1) and southwestern Tibet to the west are ophiolites (the Xigaze and Yungbwa ophiolites, respectively) which formed during Late Jurassic to Early Cretaceous time [*Gopel et al.*, 1984; *Miller et al.*, 2003]. In the Zedong area, ~270 km east of Xigaze, remnants of a Cretaceous intraoceanic arc and subduction zone are also preserved within the YZSZ [*Aitchison et al.*, 2000]. Where not overprinted by postobduction structures, the YZSZ ophiolitic belt occurs structurally above northern Tethyan Himalaya strata, or melanges which include Tethyan strata, in the hanging wall of the south directed Yarlung Zangbo Mantle thrust (YZMT) [*Tapponnier et al.*, 1981; *Burg and Chen*, 1984; *Burg et al.*, 1987; *Girardeau et al.*, 1984, 1985; *Ratschbacher et al.*, 1994]. The ophiolitic belt is inferred to have been obducted southward along the YZMT during Late Cretaceous–early Paleocene time on the basis of fossil ages in synobduction melanges, first in an intraoceanic setting and then onto the northern margin of India [*Burg and Chen*, 1984; *Burg et al.*, 1985; *Girardeau et al.*, 1984; *Searle et al.*, 1987]. Primary relationships between YZSZ rocks and those of the Gangdese forearc to the north remain cryptic because of significant modification during the India-Asia collision by the late Oligocene (30–23 Ma) north dipping Gangdese thrust system and the Miocene (19–10 Ma) south dipping Great Counter thrust system [*Ratschbacher et al.*, 1994; *Yin et al.*, 1994; *Quidelleur et al.*, 1997; *Yin et al.*, 1999; *Harrison et al.*, 2000].

2.3. Gangdese Forearc

[10] North of the YZSZ, sedimentary sequences deposited along the southern margin of Asia consist of the Cretaceous Xigaze Group and Qubeiya Formation and the lower Tertiary Tso-Jiangding Group (Figures 1 and 2) [*Liu et al.*, 1988; *Einsele et al.*, 1994; *Dürr*, 1996; *Wang et al.*, 1999]. The Xigaze Group is a >5-km-thick turbidite sequence that was deposited during the middle Cretaceous (110–84 Ma [*Wang et al.*, 1999]). The shallow-water Qubeiya Formation lies conformably on the Xigaze Group and extends to the late Maastrichtian [*Liu et al.*, 1988]. The Paleocene to lower Eocene foraminifera-bearing (i.e., *Lepidorbitoides minor* and *L. blanfordi Rao* [*Liu et al.*, 1988]) Tso-Jiangding Group is composed of interbedded limestone, sandstone, conglomerate, and minor volcanic tuff and unconformably overlies the Xigaze Group and Qubeiya Formation (Figure 2). In the Xigaze area, southern exposures of the Xigaze Group have been mapped to be depositional on the Xigaze ophiolite, suggesting that at least some YZSZ rocks represent obducted remnants of oceanic basement to the Gangdese forearc [e.g., *Burg and Chen*, 1984; *Girardeau et al.*, 1984].

2.4. Gangdese Arc

[11] The Gangdese arc of the southern Lhasa terrane comprises Cretaceous–early Tertiary calc-alkaline granitoids of the Gangdese batholith [e.g., *Schärer et al.*, 1984; *Debon et al.*, 1986] and 68 to 43 Ma nonmarine volcanic sequences of the Linzizong Formation [*Maluski et al.*, 1982; *Coulon et al.*, 1986; *Miller et al.*, 2000; *He et al.*, 2003]. The Gangdese arc is widely attributed to northward subduction of Neo-Tethys oceanic lithosphere beneath the southern Asian continental margin [e.g., *Tapponnier et al.*, 1981]. However, the presence of Oligocene and Miocene arc-like granitoids within the Gangdese arc cautions using the age of the youngest arc magmatism as a proxy for the time of collision initiation [*Harrison et al.*, 2000; *Yin and Harrison*, 2000; *Kapp et al.*, 2005a]. The Linzizong Formation is in general weakly deformed and lies unconformable on Cretaceous and older strata which have been shortened by >50% [e.g., *Burg and Chen*, 1984; *Pan*, 1993; *Murphy et al.*, 1997; *Ding and Lai*, 2003]. These relationships demonstrate that the upper crust of the Gangdese arc experienced minimal shortening during Cenozoic time.

3. Methods

[12] The aim of this study was to provide new constraints on the timing of ophiolite obduction and initial India-Asia

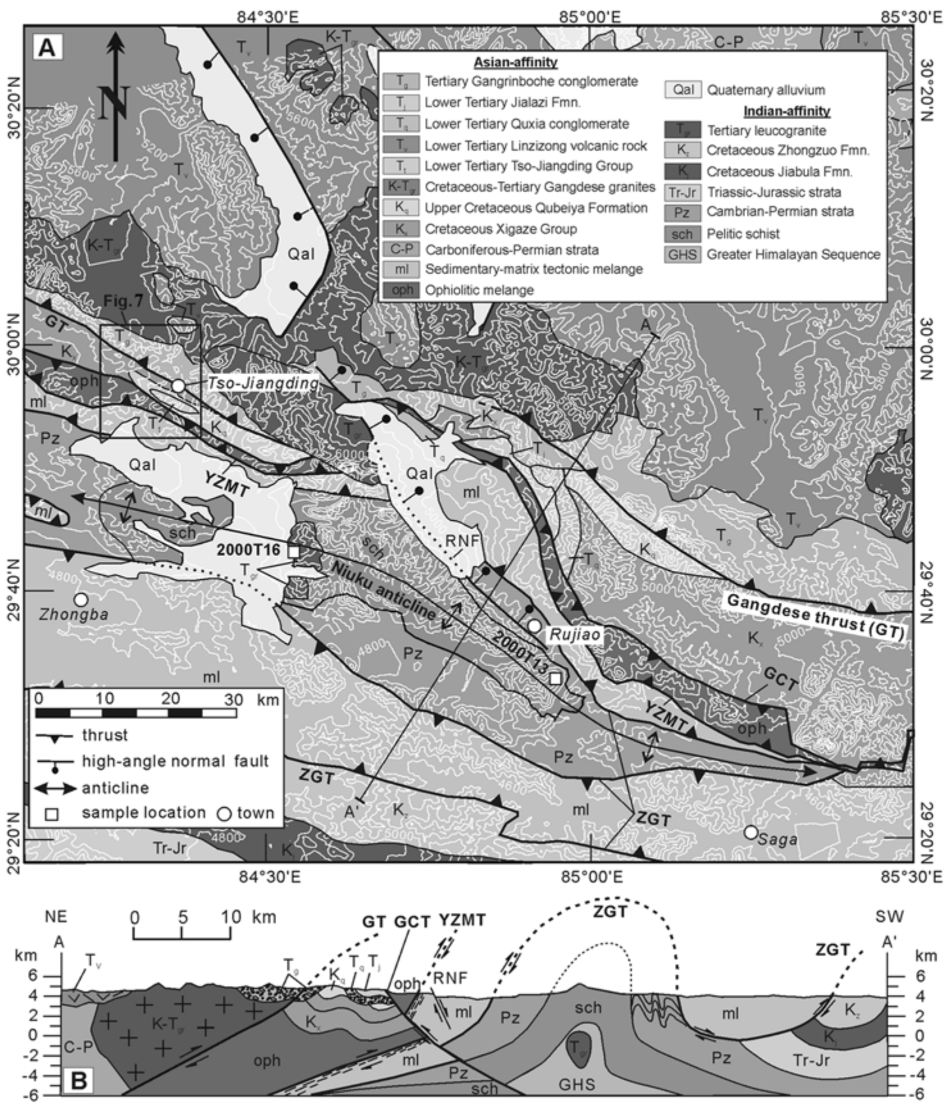

Figure 2. (a) Geologic map of the Yarlung Zangbo suture zone in south central Tibet. (b) Schematic cross section along line A-A′ shown in Figure 2a. Fault abbreviations are as follows: GCT, Great Counter thrust; GT, Gangdese thrust; RNF, Rujiao normal fault; YZMT, Yarlung Zangbo Mantle thrust; ZGT, Zhongba-Gyangze thrust. See color version of this figure at back of this issue.

collision in south central Tibet. Most of our efforts were focused west of Xigaze between Zhongba and Zheba (Figure 1), in an area spanning the YZSZ and that uniquely exposes biostratigraphically studied Upper Cretaceous–lower Tertiary marine sequences in both the Gangdese forearc region [*Liu et al.*, 1988] and the northern Tethyan Himalaya [*Wan and Ding*, 2002; *Ding*, 2003] (a summary of the biostratigraphic data is available in Table A1, auxiliary material[1]). In this study, we conducted new (1) regional geologic mapping and integrated U-Pb geochronologic and $^{40}Ar/^{39}Ar$ thermochronologic studies and (2) sedimentologic and detrital grain (zircon, muscovite, and spinel) provenance studies of the marine sequences.

[13] U-Pb zircon analyses by the isotope dilution method were determined on a VG 354 mass spectrometer at the Institute of Geology and Geophysics, Chinese Academy of Science, Beijing (IGGCAS) (Table A2 in auxiliary material). Common Pb was corrected using Pb isotopic compositions determined for K-feldspars from the same sample. Argon isotope analyses on separates of muscovite and amphibole (Table A3 in auxiliary material) were conducted on a RGA-10 mass spectrometer at IGGCAS and on a VG 1200S mass spectrometer at the University of California, Los Angeles (UCLA). Compositions of detrital spinels were determined using a CAMECA SX51 electron microprobe at IGGCAS (Table A4 in auxiliary material). U-(Th)-Pb single spot analyses on zircon were obtained using the SHRIMP II

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/tc/2004TC001729.

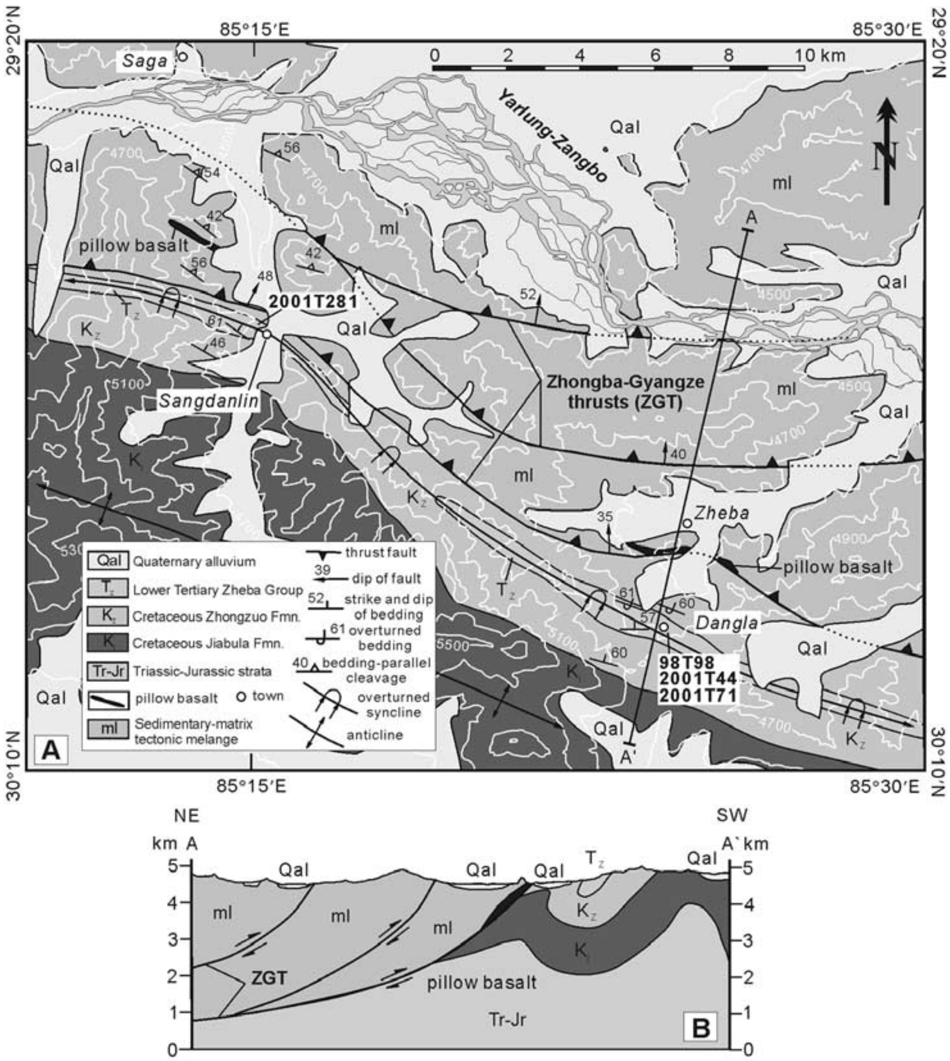

Figure 3. (a) Geologic map of the Sanganlin-Dangla area in the northern Tethyan Himalaya. (b) Schematic cross section across line A-A′ shown in Figure 3a. Fault abbreviation is ZGT, Zhongba-Gyangze thrust. See color version of this figure at back of this issue.

ion microprobe at the Chinese Academy of Geological Sciences in Beijing (Table A5 in auxiliary material) and the CAMECA ims 1270 ion microprobe at the W.M. Keck Foundation Center for Isotope Geochemistry, UCLA (Table A6 in auxiliary material). Ion microprobe analyses were corrected for common Pb using measured ^{204}Pb and an isotopic composition estimated from the Pb evolution model of *Stacey and Kramers* [1975]. Additional information regarding analytical methods and procedures is available as auxiliary material.

4. Structure and Geochronology

4.1. Zhongba-Gyangze Thrust System

[14] In south central Tibet, northern Tethyan Himalaya strata are disrupted by the >500-km-long Zhongba-Gyangze thrust system (Figures 1, 2, and 3), which is equivalent to the Sheru and Gyangze thrusts further to the east [*Ratschbacher et al.*, 1994]. The thrust system juxtaposes sedimentary-matrix melange in the hanging wall against northern Tethyan Himalayan strata in the footwall (Figures 1, 2, and 3). The melange is characterized by tectonically dismembered Triassic to Cretaceous stratigraphic units and exotic blocks of Carboniferous-Permian limestone within a strongly deformed matrix of sandstone and siliceous shale. It is likely correlative with sedimentary-matrix melanges along-strike to the east which are interpreted to have been derived from water-saturated Tethyan Himalaya strata and tectonized during southward obduction of oceanic rocks onto the Indian margin [e.g., *Qian*, 1982; *Burg and Chen*, 1984; *Aitchison et al.*, 2000]. Field observations during this study, and previous work [*Burg and Chen*, 1984; *Ratschbacher et al.*, 1994], show that

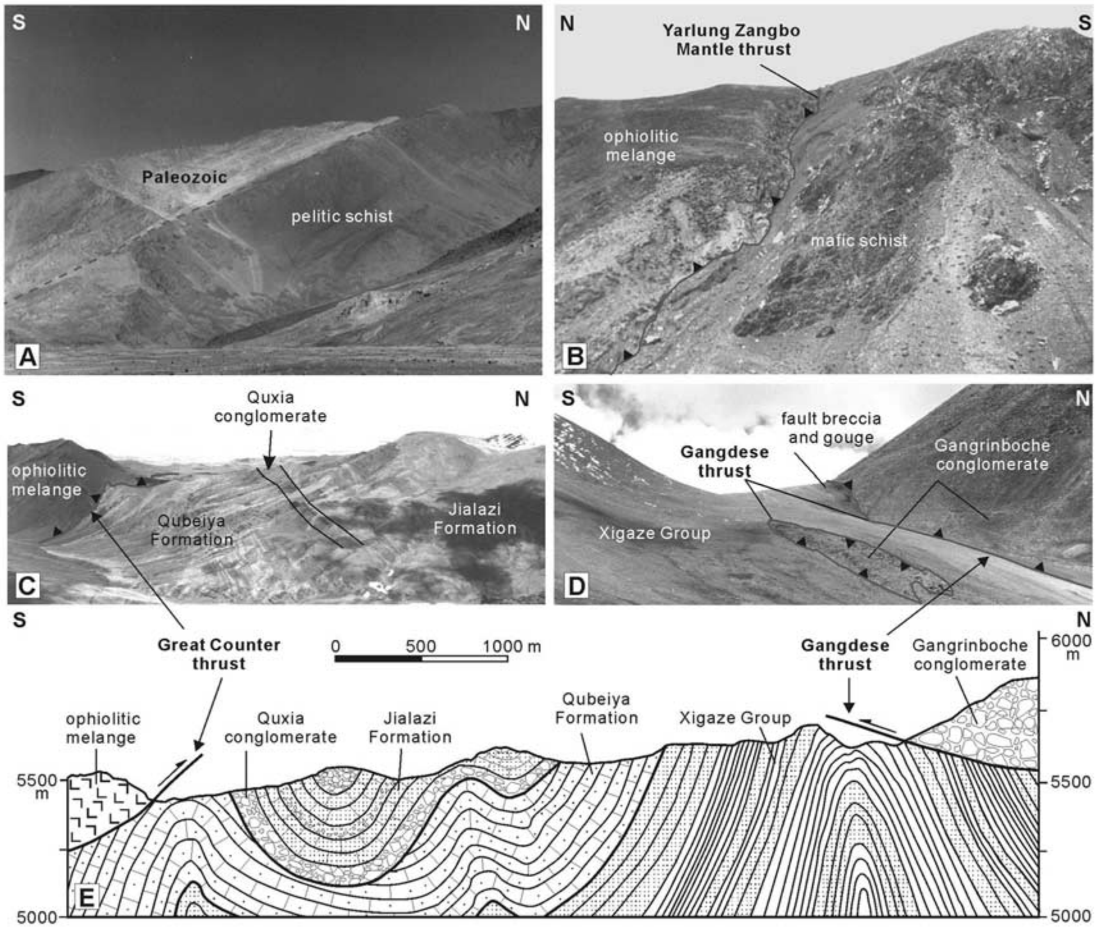

Figure 4. (a) View of the southern limb of the Niuku antiform looking toward the west. Here Paleozoic metasandstone and metalimestone overlie pelitic schist. The sample dated in this study (2000T13) was collected from this exposure in the Rujiao area (Figure 2). (b) View of the north dipping Yarlung Zangbo Mantle thrust looking toward the east in the Sangsang area (Figure 1). The thrust juxtaposes ophiolitic melange in the hanging wall against a fault zone sliver of amphibole-bearing mafic schist in the footwall. Samples 2001T77, 2001T80, and 2001T82 were collected from this outcrop (Figure 1). (c) View toward the west of the south dipping Great Counter thrust in the Tso-Jiangding area (Figure 7), with ophiolitic melange in the hanging wall and the lower Tertiary Qubeiya Formation, Quxia conglomerate, and Jialazi Formation in the footwall. (d) View of the Gangdese thrust looking toward the west in the Tso-Jiangding area. The Gangdese thrust juxtaposes the Gangrinboche conglomerate in the hanging wall against the Xigaze Group in the footwall. (e) Cross section showing the major structures in the Tso-Jiangding area, including the angular unconformity beneath the Quxia conglomerate. See color version of this figure at back of this issue.

the Zhongba-Gyangze thrust system is characterized by top-to-the-south sense-of-shear, as indicated by south vergent mesoscale folds in the footwall northern Tethyan Himalaya strata. Near Zhongba, the Zhongba-Gyangze thrust is folded by the south vergent, doubly plunging E-W Niuku anticline, which is cored by pelitic schist and conformably overlying Devonian to Permian limestone (Figures 2 and 4a).

[15] Timing of deformation within the northern Tethyan Himalaya is inferred from U-Pb and $^{40}Ar/^{39}Ar$ studies on rocks in the core of the Niuku anticline. Five zircons from a sample of undeformed leucogranite that intrudes into pelitic schist in the core of the Niuku anticline (2000T16; Figure 2) yields concordant to slightly discordant U-Pb ages between 45 and 51 Ma (Figure 5a). We interpret the youngest concordant zircon age of $\sim$45 Ma as the crystallization age for the leucogranite, with the older ages being attributed to inheritance. Muscovite from a sample of the host quartz + biotite + muscovite + chorite + albite schist (2000T13; Figure 2) yields a fairly flat $^{40}Ar/^{39}Ar$ age spectrum over the last $\sim$80% cumulative ^{39}Ar released with a weighted mean age of 41 ± 2 Ma (2σ; Figure 6a). We attribute crustal

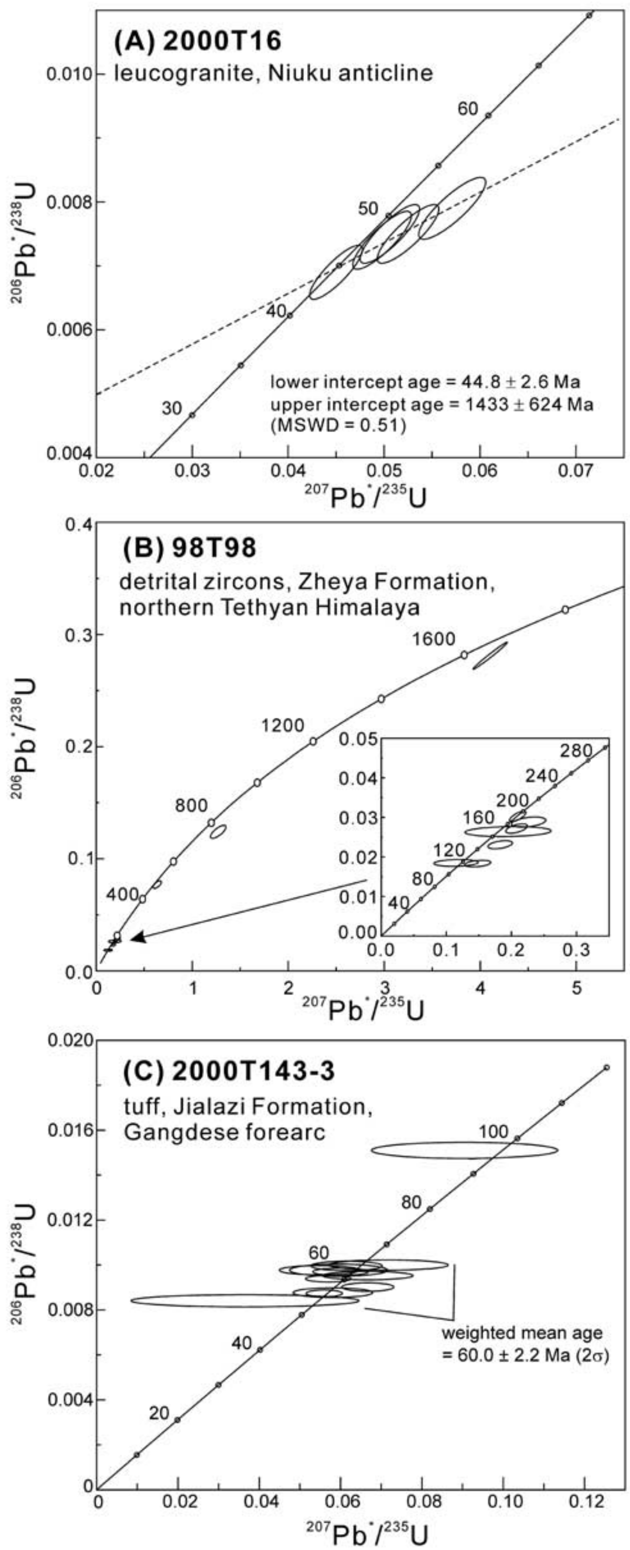

Figure 5. U-Pb concordia diagrams showing zircon dating results. Error ellipses are 2σ.

anatexis and exhumation in the northern Tethyan Himalaya between 45 and 41 Ma to be consequences of middle Eocene crustal thickening following development of the Zhongba-Gyangze thrust system. This interpretation suggests initiation of shortening prior to ~45 Ma in the northern Tethyan Himalaya, consistent with K-Ar ages of 50–47 Ma for metamorphic, synkinematic muscovite within a north dipping shear zone ~250 km to the east [*Ratschbacher et al.*, 1994].

4.2. Yarlung Zangbo Mantle Thrust

[16] The Yarlung Zangbo Mantle thrust (YZMT) places ophiolitic melange in the hanging wall southward over the sedimentary-matrix melange in the footwall (Figures 1, 2, and 7). The ophiolitic melange is characterized by blocks of sandstone, chert, siliceous shale, limestone, basalt and ultramafic rocks, interpreted to be fragments of accretionary prism and trench rocks, within a strongly deformed matrix of serpentinite, sandstone, and siliceous shale. The YZMT is characterized by a 1–3-km-thick mylonitic shear zone. Small-scale south verging folds and asymmetric boudinage structures indicate a top-to-south sense-of-shear. Mafic schist (amphibole + phengitic muscovite + chlorite + albite + sphene + relic clinopyroxene ± olivine) locally occurs as a tectonic sliver within the YZMT zone (Figures 1 and 4b). Amphibole consists of needle-shaped crystals of magnesio-riebeckite composition. Significant mineral zoning and retrograde overprints were not observed. Three amphibole separates (2001T77, 2001T80, and 2001T82; Figure 1) yield $^{40}Ar/^{39}Ar$ age spectra with weighted mean plateau ages of 62.8 ± 0.8 Ma, 63.4 ± 1.3 Ma, and 63.2 ± 0.7 Ma (Figures 6b–6d and auxiliary Table A3), respectively. We interpret these ages to indicate exhumation-related cooling of the mafic schist during early Paleocene time, presumably during slip along the YZMT and southward obduction of ophiolitic melange.

4.3. Great Counter Thrust and Gangdese Thrust

[17] North of the YZSZ, Cretaceous Gangdese forearc strata occur in the footwall of the south dipping Great Counter thrust (GCT) to the south and the north dipping Gangdese thrust (GT) to the north (Figures 1, 2, 4c–4e, and 7). The GCT juxtaposes YZSZ ophiolitic melange in the hanging wall. In the Tso-Jiangding area (Figure 7), it is characterized by an approximately meter-thick zone of strongly brecciated basalt and chert and foliated serpentinized ultramafic rocks. Slickenlines together with steps on fibrous calcite minerals along brittle fault surfaces within the fault breccia indicate top-to-the-north sense-of-shear. Miocene slip along the GCT [*Ratschbacher et al.*, 1994; *Quidelleur et al.*, 1997; *Yin et al.*, 1999; *Harrison et al.*, 2000] significantly postdates exhumation of mafic schists within the YZMT during early Paleocene time, but overlaps at least partly with the timing of slip on the south Tibetan detachment system (STDS) to the south [e.g., *Burchfiel et al.*, 1992; *Hodges*, 2000]. Therefore we interpret the GCT to cut the YZMT (Figures 2b and 7b), and following *Yin et al.* [1999],

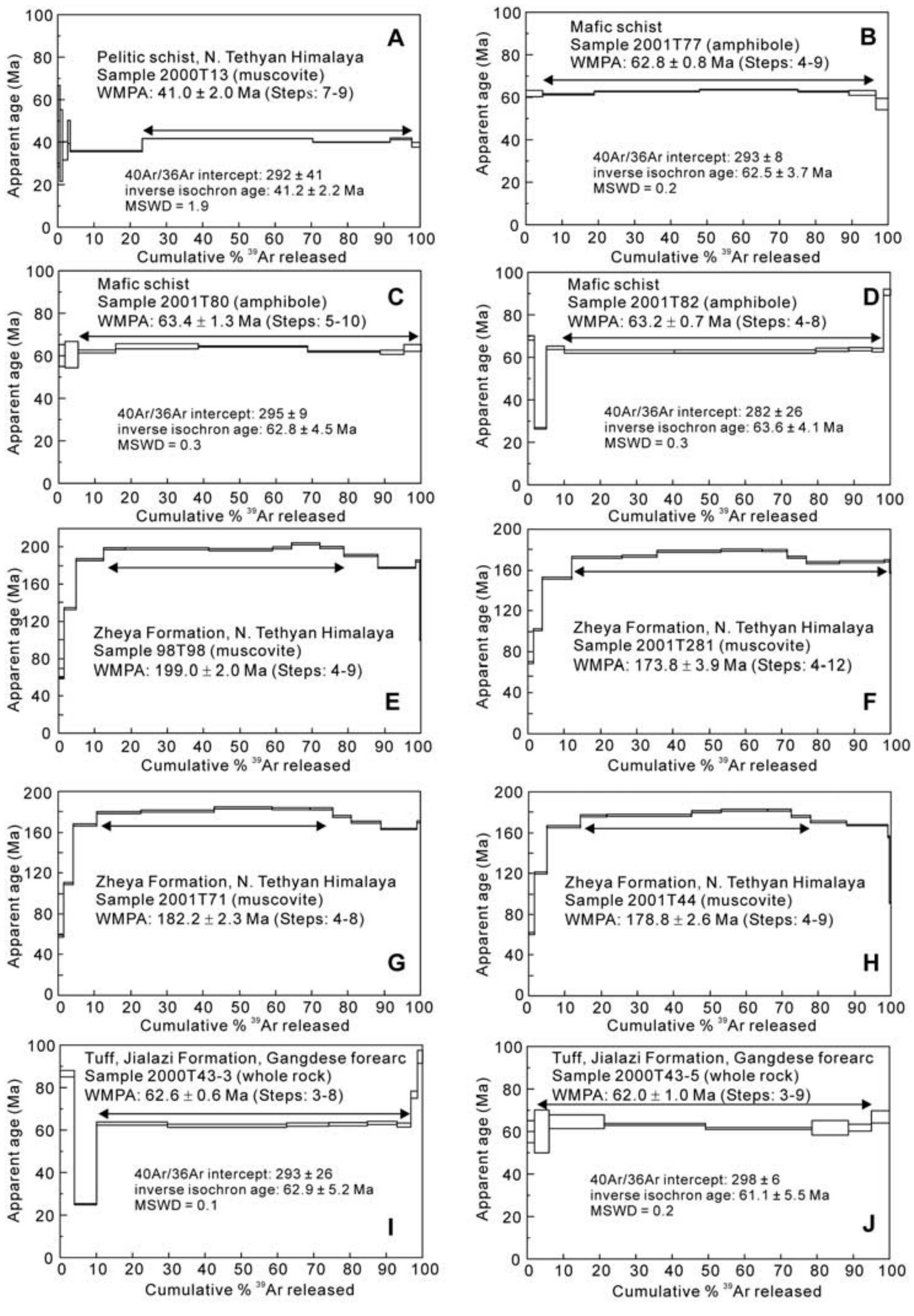

Figure 6. The $^{40}Ar/^{39}Ar$ age spectra. Uncertainties for weighted mean plateau ages (WMPA) are 2σ. Also provided are $^{40}Ar/^{36}Ar$ intercept values and inverse isochron ages for all of the nondetrital samples.

to root at depth into a decollement that is linked with the STDS.

[18] The GT places the Gangdese arc and unconformably overlying Tertiary conglomerates in the hanging wall southward over Cretaceous Gangdese forearc strata (Figures 1, 2, 4d–4e, and 7). Near Tso-Jiangding (Figures 4e and 7), footwall Cretaceous strata are deformed by predominantly south verging kilometer-scale folds which accommodated ∼4 km (∼44% over a present-day north-south distance of 5 km) shortening. Along strike to the east in the Zedong area and to the west in the Kailas area, timing of slip on the GT has been inferred from previous U-Pb geochronologic and $^{40}Ar/^{39}Ar$ thermochronologic studies to be between 30 and 23 Ma [*Yin et al.*, 1994;

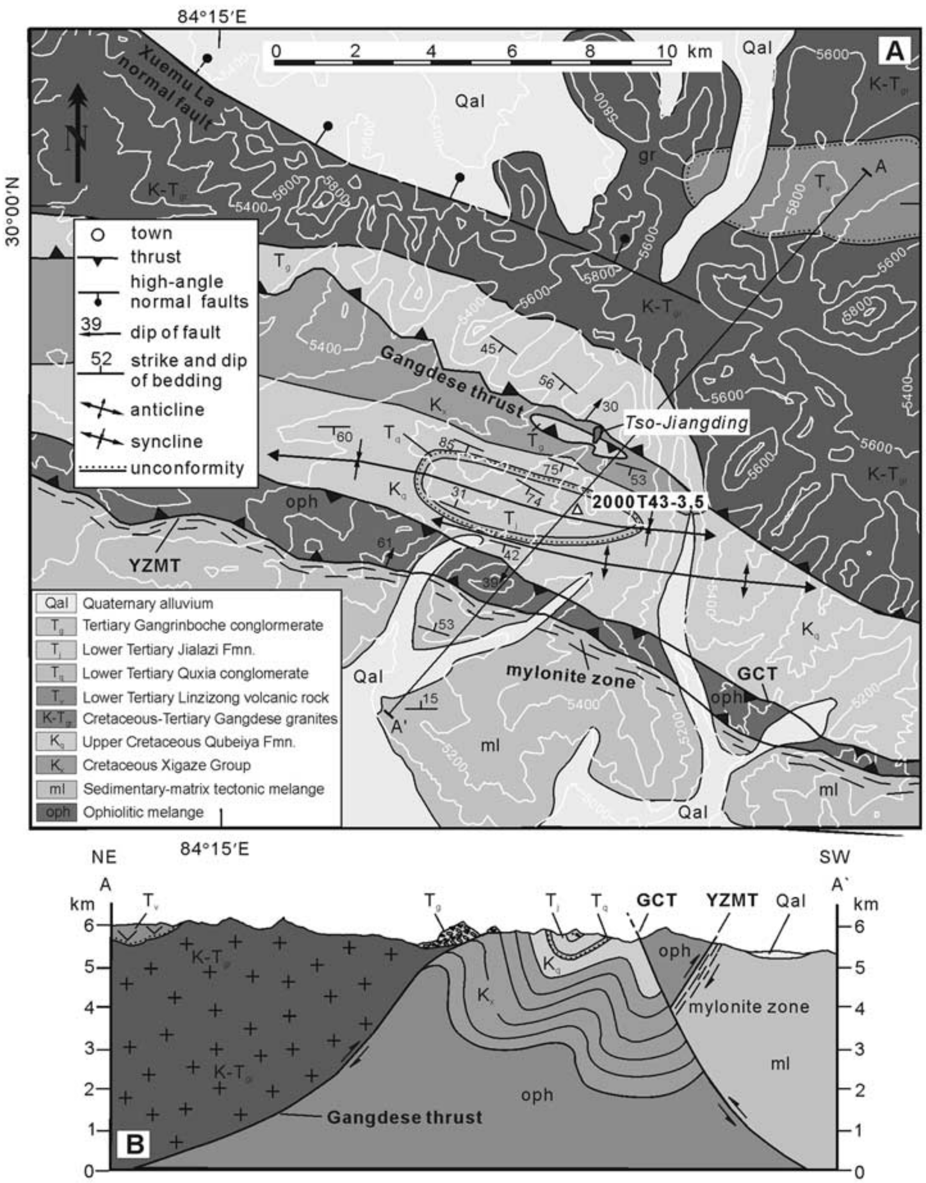

Figure 7. (a) Geologic map of Tso-Jiangding area in southern Tibet. (b) Schematic cross section along line A-A′ shown in Figure 7a. Fault abbreviations are as follows: GCT, Great Counter thrust; YZMT, Yarlung Zangbo Mantle thrust. See color version of this figure at back of this issue.

Quidelleur et al., 1997; *Yin et al.*, 1999; *Harrison et al.*, 2000].

5. Cretaceous–Lower Tertiary Marine Sequences

5.1. Northern Tethyan Himalaya: Sangdanlin-Dangla Area

[19] The studied uppermost Cretaceous–lower Tertiary sequences in the northern Tethyan Himalaya are exposed directly south of the Zhongba-Gyangze thrust system near Sangdanlin and Dangla (Figure 3). They consist of the Upper Cretaceous Zhongzuo Formation (K_Z) and overlying lower Tertiary Zheba Group (T_Z), which is divided into the older Sangdanlin Formation and the younger Zheya Formation (Figure 8) [*Ding*, 2003]. The Zhongzuo Formation is characterized by hemipelagic shale, chert, siltstone, limestone, and intercalated quartz-rich sandstone and pebbly sandstone. Cross-bed measurements (n = 34) indicate a northerly paleocurrent direction (Figure 8). The youngest age of the Zhongzuo Formation is constrained by planktonic foraminifera recovered from pelagic carbonate at the top of the section exposed near Zheba and Sangdanlin (Figure 8) which are assigned to the upper *G. gansseri* and lower *A. mayaroensis* zones of the Late Cretaceous (68–70 Ma) [*Wan and Ding*, 2002].

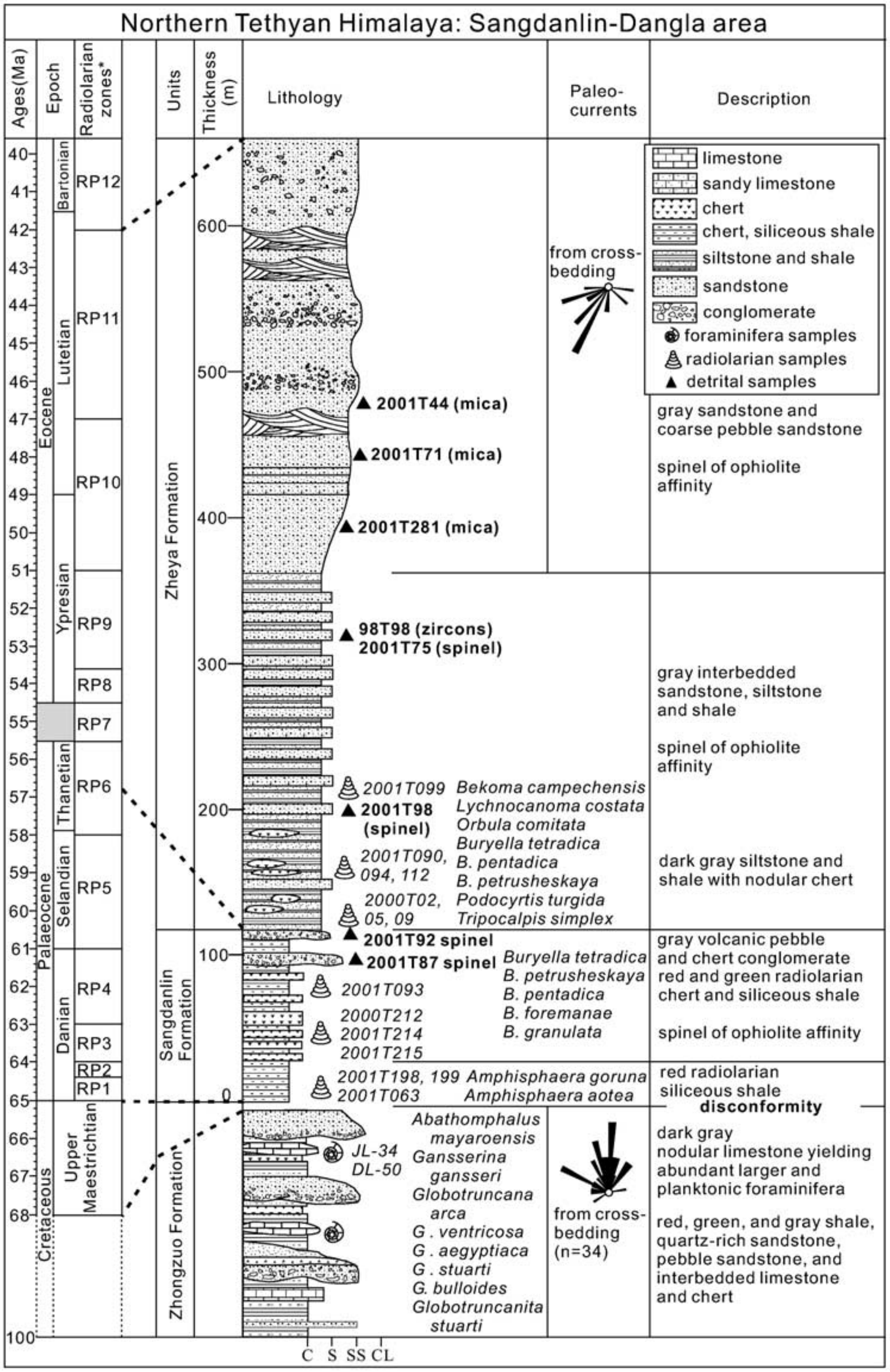

Figure 8. Stratigraphic column for Upper Cretaceous–lower Tertiary sequences in the Sandanlin-Dangla area. Samples analyzed in this study are shown in bold. The locations and names (italics) of fossil samples studied by *Wan and Ding* [2002] and *Ding* [2003] are also shown (see auxiliary Table A1 for a summary of the biostratigraphic data and the original references for additional documentation, including images of diagnostic fossils). Timescale after *Berggren et al.* [1995].

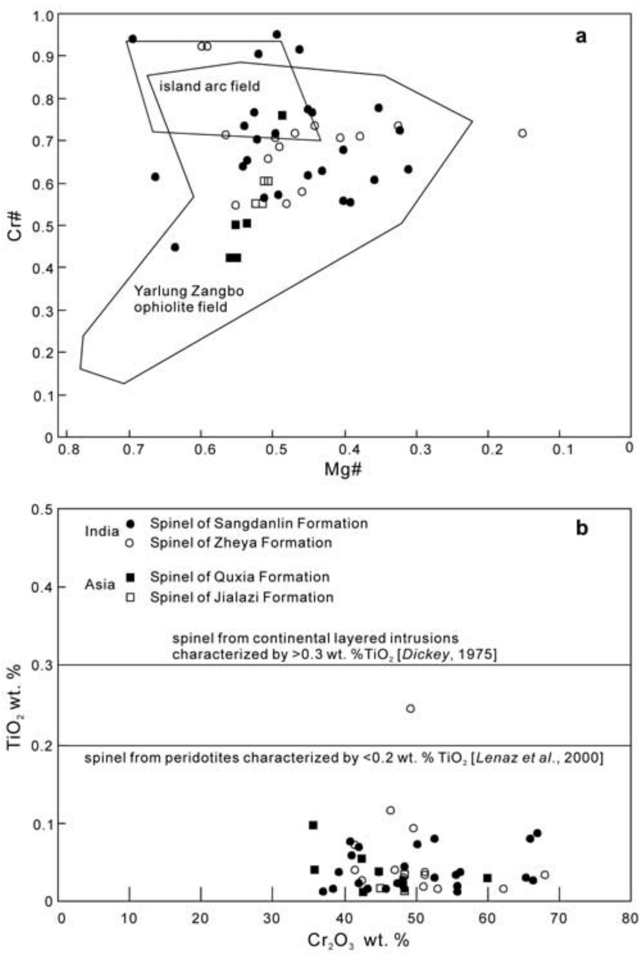

Figure 9. (a) Cr [Cr/(Al + Cr)] versus Mg [Mg/(Mg + Fe^{2+})] and (b) TiO_2 weight percent versus $Cr_2 0_3$ weight percent diagrams for detrital chromium spinel. The Yarlung Zangbo ophiolite field is based on analyses of *Wang et al.* [1987] and *Wang et al.* [1999]; island arc field is from *Dick and Bullen* [1984].

[20] The lower Tertiary Zheba Group coarsens upward from mainly radiolarian siliceous shale and chert in the Sangdanlin and lower part of the Zheya Formation to pebbly sandstone in the upper part of the Zheya Formation (Figure 8). The Zheya Formation is distinguished from the Sangdanlin Formation by the presence of dark grey, fine-grained clastic-rich layers. The 100–150-m-thick Sangdanlin Formation consists of red and green siliceous shale and radiolarian chert. Its age ranges from Danian to Thanetian (65–55 Ma [*Ding*, 2003]) on the basis of the presence of radiolarian zones: *Amphisphaera aotea*, *A. Kina*, *Buryella granulata*, *B. foremanae*, *Buryella tetradica* and *Bekoma campechensis* (radiolarian zone RP1 to RP6 [*Hollis*, 1997]). Although the contact with the underlying Zhongzuo Formation appears conformable, there is a gap in time between the youngest age determined for the Zhongzuo Formation (68–70 Ma) and the oldest age determined for the Sangdanlin Formation (∼65 Ma), which may indicate the presence of a disconformity. Two beds of conglomerate, dominated by clasts of volcanic rock and chert, occur in the upper part of the Sangdanlin Formation (Figure 8). The lower part of Zheya Formation consists of a >200-m-thick sequence of turbidites, characterized by lithic sandstone (with volcanic, chert, sandstone, shale, and ultramafic clasts) and sandy shale interbedded with numerous radiolarian cherts. It is late Paleocene in age on the basis of the presence of the radiolarian *Bekoma campechensis* [*Ding*, 2003]. The upper part of the Zheya Formation consists of pebbly sandstone and subordinate conglomerate with clasts of volcanic rock, chert, sandstone, and shale. Biostratigraphic age control is lacking. However, considering that it conformably overlies the lower part of the Zheya Formation and is unlikely to be younger than the youngest marine strata documented in the Tethyan Himalaya (Lutetian) [*Wen*, 1987a, 1987b; *Willems et al.*, 1996; *Xu*, 2000], we infer a Thanetian to Lutetian age.

[21] Spinels were identified in thin sections of sandstones from both the Sangdanlin (the first appearance being in sample 2001T87; Figure 8) and Zheya Formations, but not in sandstones of the underlying Zhongzuo Formation. Spinel compositions are characterized by high Cr [Cr/(Al + Cr)] of >0.4 and low TiO_2 wt. % (generally <0.1) (Figure 9). They are similar in composition to spinels in YZSZ ophiolites [*Wang et al.*, 1987; *Wang et al.*, 1999] and from supra-subduction zone harzburgites in general [e.g., *Dick and Bullen*, 1984; *Lenaz et al.*, 2000] (Figure 9).

[22] U-Pb ages on 10 detrital zircons from the Zheya Formation (sample 98T98; Figures 3 and 8) were obtained using the SHRIMP II ion microprobe (Figure 5b). Of the three oldest zircons, one is nearly concordant at ∼478 Ma and the other two are discordant with $^{207}Pb^*/^{206}Pb^*$ ages of ∼1050 Ma and ∼1730 Ma. Younger zircons provide $^{206}Pb^*/^{238}U$ ages between 200–140 Ma (n = 5) and ∼120 Ma (n = 2). High Th/U ratios of 0.4–0.7 and strong oscillatory zoning observed in cathodoluminescence images are consistent with the detrital zircons being of igneous origin. The $^{40}Ar/^{39}Ar$ step-heating experiments were also conducted on four detrital muscovite separates (98T98, 2001T281, 2001T71, and 2001T44; Figures 3 and 8) from micaceous sandstones in the Zheya Formation. A single result would be geologically meaningless because of the possibility of mixing muscovite with very different ages. However, all four samples yield similar age spectra with significant age gradients over the first ∼15% cumulative ^{39}Ar released followed by relatively flat spectra with apparent ages between ∼170 and 200 Ma (auxiliary Table A3 and Figures 6g–6j). These ages are significantly older than the age of deposition, ruling out the possibility that they were reset during burial or subsequent deformation, and are in the range of one group of detrital zircon ages (140–200 Ma).

5.2. Gandese Forearc Region: Tso-Jiangding Area

[23] North of the YZSZ in the Tso-Jiangding area, the lower Tertiary Tso-Jiangding Group (T_t) unconformably overlies the Upper Cretaceous Qubeiya Formation (K_q) and underlying Xigaze Group (K_x) (Figures 2 and 7). The Tso-Jiangding Group is divided into the Quxia conglomerate (T_q) in its lower part and the Jialazi Formation (T_j) in its upper part.

[24] In contrast to the dark gray shale, sandstone, and channel conglomerate of the Xigaze Group exposed in the Xigaze area (Figure 1) [*Einsele et al.*, 1994; *Dürr*, 1996], the Xigaze Group near Tso-Jiangding consists of green and red shale and sandstone with rare channel conglomerate. We interpret these sequences to be in the upper part of the Xigaze Group. Measurements of sole structures (n = 15) indicate a southerly paleocurrent direction (Figure 10), similar to that determined for the Xigaze Group near Xigaze [*Einsele et al.*, 1994; *Dürr*, 1996]. Conformably overlying the Xigaze Group is yellow sandy and marly shallow-marine limestone of the Qubeiya Formation. The Qubeiya Formation includes abundant large foraminifera (Figure 10), suggesting a late Campanian to late Maastrichtian age [*Liu et al.*, 1988].

[25] The 50–100-m-thick Quxia conglomerate is separated from the underlying Qubeiya Formation and Xigaze Group by an angular unconformity (Figures 1 and 4e). Pebbles consist of granitoid (20%), volcanic rock (20%), limestone (10%), chert (45%), and ultramafic rock (5%). Chromium-rich spinel was observed in all thin sections of sandstone and their compositions are similar to those of ophiolite affinity in the northern Tethyan Himalaya Zheba Group (Figure 9). Pebble imbrications indicate a bimodal paleocurrent direction with mean vectors of 191° (n = 25) and 336° (n = 28) (Figure 10).

[26] The Jialazi Formation conformably overlies the Quxia conglomerate and consists mainly of foraminifera-bearing sandy limestone and interbedded conglomerate and sandstone (Figure 10). It defines the youngest marine strata observed along the YZSZ in south central Tibet. The lower and upper parts of the Jialazi Formation include foraminifera which belong to the *Miscellanea-Daviesina* and *Nummulites-Discocyclina* faunas, respectively [*Liu et al.*, 1988]. These faunas are the same as those observed for the Zhepure (or Zongpu) Formation of the Tethyan Himalaya in the Gamba and Tingri areas [*He et al.*, 1976; *Wen*, 1987a, 1987b; *Willems et al.*, 1996], and suggest a Paleocene to early Eocene age. Chromium-rich spinels were documented in sandstones and sandy limestones of the Jialazi Formation and are of similar compositions to those in the underlying Quxia conglomerate (Figure 9).

[27] A 10-m-thick, well-lithified, volcanic tuff layer occurs in the lower part of the Jialazi Formation (Figure 8). Two whole rock $^{40}Ar/^{39}Ar$ analyses of the tuff (2000T43-3 and 2000T43-5) yield weighted mean plateau ages of 62.6 ± 0.6 Ma and 62.0 ± 1.0 Ma (auxiliary Table A4 and Figures 6i–6j), respectively. Zircons from one tuff sample (2000T43-3) provide a cluster of concordant U-Pb analyses (n = 11) with a weighted mean age of 60.0 ± 2.2 Ma, statistically indistinguishable from the $^{40}Ar/^{39}Ar$ ages, and one inherited age of ∼97 Ma (Figure 5c and auxiliary Table A6). These results, together with biostratigraphic evidence that the Qubeiya Formation is late Maastrichtian, constrain the age of the Quxia conglomerate and underlying unconformity to be younger than late Maastrichtian but older than ∼62 Ma.

[28] North of the GT, a >1000-m-thick sequence of nonmarine conglomerate and trough cross-stratified sandstone (Tg) which includes plant fragments unconformably overlies Cretaceous–Tertiary igneous rocks of the Gangdese arc (Figures 2, 7, and 10). The conglomerate is dominated by subangular to well-rounded clasts of granitic composition, most likely derived from the underlying Gangdese batholith. Imbricated pebbles indicate a southerly paleocurrent direction (n = 42; Figure 10). Similar coarse clastic deposits are exposed semicontinuously along the entire length of the northern margin of the YZSZ and have been named the Gangrinboche conglomerate [*Aitchison et al.*, 2002]. Although these conglomerates are widely cited to be as old as Eocene in age, field relations and reevaluation of previous biostratigraphic studies suggest a late Oligocene–early Miocene age [*Aitchison et al.*, 2002, and references therein]. Our observations that the conglomerates are cut by, and occur both in the hanging wall and footwall of the GT (Figure 2), are consistent with conglomerate deposition during Oligocene-Miocene slip along the GT [e.g., *Yin et al.*, 1999].

6. Discussion

6.1. Timing of Ophiolite Obduction

[29] There is substantial evidence that ophiolitic rocks were obducted onto the northwestern margin of India during latest Cretaceous–earliest Tertiary time [e.g., *Searle*, 1983; *Beck et al.*, 1996; *Gnos et al.*, 1997; *Searle et al.*, 1997]. While an obduction event of similar age has been suggested for southern Tibet [*Allègre et al.*, 1984; *Burg and Chen*, 1984; *Burg et al.*, 1987; *Makovsky et al.*, 1999; *Aitchison et al.*, 2000; *Davis et al.*, 2002], supporting geochronologic and stratigraphic evidence has remained scarce. We suggest that $^{40}Ar/^{39}Ar$ ages of ∼63 Ma for hornblende from mafic schist within the YZMT provide new evidence for southward obduction of ophiolitic rocks during this time. Within the northern Tethyan Himalaya, the Upper Cretaceous Zhongzuo Formation includes shallow-water foraminifera-bearing limestones and quartz-rich sandstones which lack detrital spinel. It is overlain by Paleocene deepwater siliceous sedimentary rocks of the lower part of the Sangdanlin Formation. Detrital spinel of ophiolite affinity was identified in the first clastic deposit in the upper part of the Sangdanlin Formation (Figure 8). We suggest that the transition from Zhongzuo Formation to Sangdanlin Formation deposition between ∼68–65 Ma records the initiation of southward obduction of ophiolitic materials onto the northern Indian margin, which would have resulted in loading and flexural subsidence of the northern Tethyan Himalaya to below the carbonate compensation depth and provided a source for the detrital spinel. Although detrital spinels have not been documented to the south in the Gamba-Tingri area, a similar transition from shallow-water to deepwater deposition [*Willems et al.*, 1996; *Wan et al.*, 2000] and onset of increased subsidence [*Rowley*, 1998] between 68 and 65 Ma may be signatures of this obduction event.

6.2. Uplift History of the Gangdese Forearc

[30] The Gangdese forearc basin was filled by a shallowing upward megasequence during the Cretaceous, from the

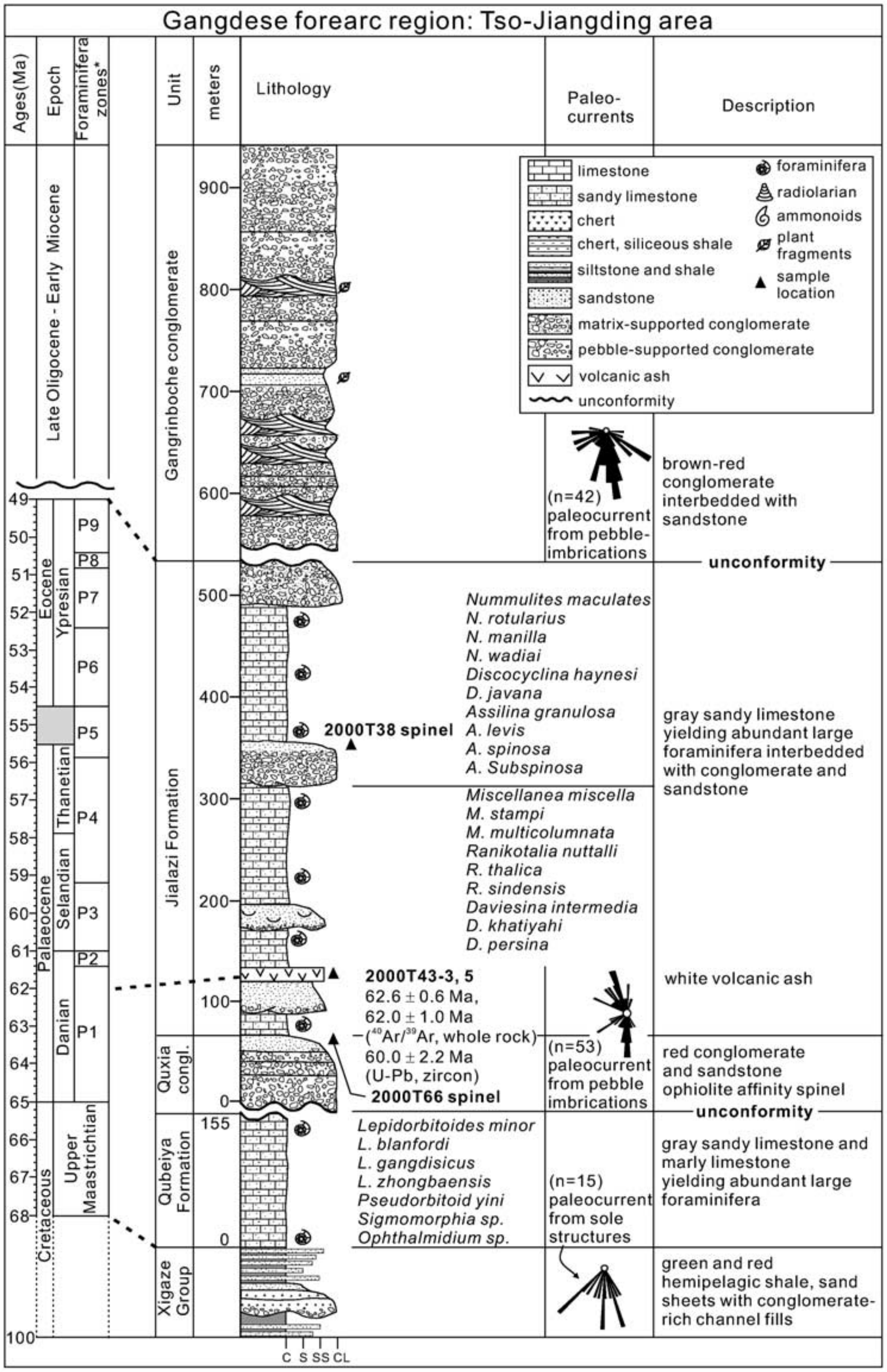

Figure 10. Stratigraphic column for Upper Cretaceous–lower Tertiary sequences in the Tso-Jiangding area. Timescale after *Berggren et al.* [1995].

deep marine Xigaze Group turbidites to shallow shelf sandy limestone of the upper Campanian to upper Maastrichtian Qubeiya Formation. Onset of shallow marine deposition predates that within the Gangdese forearc to the west in Ladakh (Paleocene [*Garzanti and Haver*, 1988]). Additionally, the Gangdese forearc in south central Tibet experienced an episode of deformation subsequent to late Maastrichtian time but before ~62 Ma, as evidenced by the development of an angular unconformity during this time beneath the Quxia conglomerate. This deformation was coeval with southward obduction of ophiolitic rocks onto the northern Indian margin and development of an angular unconformity beneath Linzizong volcanic rocks in the Lhasa terrane to the north. It may also have resulted in uplift of the Gangdese subduction-accretion complex, as suggested by both southerly and northerly paleocurrents and clasts of chert, ultramafic fragments, and chromium-rich spinel in the Quxia conglomerate. Marine deposition continued within the Gandese forearc region until at least early Eocene time. The precise timing of uplift of the Gangdese forearc to above sea level is not recorded in the stratigraphic record, but must have occurred prior to deposition of the Gangrinboche conglomerate during late Oligocene–early Miocene (?) time.

6.3. Minimum Age of India-Asia Collision

[31] There are no documented sources for detrital zircons (~120 Ma and 200–150 Ma) and muscovites (~200–170 Ma) in northerly derived sandstones from the upper part of the Thanetian to Lutetian Zheya Formation south of the YZSZ. However, 200–120 Ma granitoids have been documented north of the YZSZ in the Nyainqentanglha Shan ~90 km northwest of Lhasa [*Kapp et al.*, 2005a], in the northern Lhasa terrane [*Xu et al.*, 1985; *Harris et al.*, 1988; *Murphy et al.*, 1997], and in the Qiangtang terrane [*Kapp et al.*, 2003, 2005b]. Furthermore, micas from the Amdo gneiss along the Bangong suture and from Carboniferous micaceous sandstones in the central Qiangtang terrane yield $^{40}Ar/^{39}Ar$ cooling ages between 180 and 160 Ma [*Guynn et al.*, 2003; *Kapp et al.*, 2005b]. *Dürr* [1996] proposed that metamorphic fragments in the Cretaceous Xigaze Group were derived from the Qiangtang terrane. Here we suggest that detritus of Asian affinity was being transported as far south as the northern Tethyan Himalaya, and therefore that India must have collided with Asia, by Lutetian time.

6.4. Tectonic Models

[32] In the following, we present two contrasting models for the closure history of the Neo-Tethys Ocean in south central Tibet. Both can explain the following events at ~65 Ma: (1) initial southward obduction of oceanic rocks onto the northern Indian margin, (2) subsidence of the northern Tethyan Himalaya and deformation of the Gangdese forearc, along with input of detrital spinel of ophiolite affinity into both basins, and (3) onset of voluminous Linzizong volcanism.

6.4.1. Obduction Marks Initiation of India-Asia Collision

[33] Oceanic rocks obducted onto the northern margin of India in south central Tibet may have included subduction-accretion rocks and structurally overlying oceanic basement to the Gangdese forearc basin (Figure 11a). This hypothesis suggests onset of tectonic interaction between the Indian and Asian continental margins by ~65 Ma. The Gangdese ocean-continent subduction system in south central Tibet may have become intraoceanic to the east and west (Figure 11b; compare to similar tectonic reconstruction proposed by *Beck et al.* [1996]), which could explain intraoceanic ophiolitic, subduction-accretion, and arc fragments near Zedong [*Aitchison et al.*, 2000; *Davis et al.*, 2002] and in the western Himalaya [e.g., *Searle et al.*, 1987; *Gnos et al.*, 1997]. An intraoceanic subduction system may have separated India and Asia prior to ~65 Ma [e.g., *Beck et al.*, 1996]; however, there is no evidence in the geologic and stratigraphic record of south central Tibet for its former existence or obduction onto the Indian margin. Onset of collision at ~65 Ma may have induced rollback of a formerly shallow subducting Neo-Tethys oceanic slab, with associated asthenospheric upwelling initiating Linzizong volcanism (Figure 11a) [*Ding et al.*, 2003]. In the Tingri region (Figure 1), tectonic subsidence increased between 68 and 65 Ma, persisted until ~55 Ma, and was minimal during early and middle Eocene time [*Rowley*, 1998]. Ophiolite obduction and onset of India-Asian collision at ~65 Ma could explain the coeval acceleration in tectonic subsidence. The decrease in tectonic subsidence at ~55 Ma may mark the time when collision-related deformation propagated southward into the Tethyan Himalaya. By late middle Eocene time (between 45 and 41 Ma), crustal thickening related to this deformation resulted in crustal anatexis and exhumation [*Ratschbacher et al.*, 1994; this study] and the cessation of marine deposition [e.g., *Willems et al.*, 1996]. An early India-Asia collision has been challenged in part because of the persistence of marine conditions until Lutetian time [e.g., *Aitchison et al.*, 2002; *Aitchison and Davis*, 2004]. However, this may be attributed to the subduction of a thin Greater Indian passive margin [*Yin and Harrison*, 2000]. This model can explain all of the major lithotectonic assemblages and tectonic events that have been recognized in south central Tibet (Figure 11a). However, it challenges the current paradigm of Eocene collision initiation and makes profound predictions concerning the magnitude of Paleocene intracontinental shortening.

[34] The paleoposition of India throughout Cenozoic time is reasonably well constrained from reconstruction of marine magnetic anomalies and apparent polar wander paths determined from paleomagnetic studies [e.g., *Patriat and Achache*, 1984; *Dewey et al.*, 1989; *Klootwijk et al.*, 1992; *Lee and Lawver*, 1995]. Less clear, but just as fundamental for accurately estimating the initiation age of India-Asia collision, are the original shape and extent of Greater India and the paleoposition of the southern Asian margin during earliest Tertiary time. Greater India could have been enormous, similar in area and shape to the present-day Tibetan Plateau, on the basis of reconstructions of Gondwana and shortening estimates with the Himalayan fold-thrust belt [e.g., *Veevers et al.*, 1975; *Lee and Lawver*, 1995; *DeCelles et al.*, 2002]. The most direct constraints on the position of the Tethyan Himalaya and Lhasa terrane in south central Tibet are provided by paleomagnetic studies of Linzizong volcanic rocks near Lhasa and Paleocene sedimentary sequences in the Gamba-Tingri area (see *Liu and Einsele* [1994] for compilation and references). Despite significant scatter in paleolatitude estimates, possibly due to secondary remagnetizations and age uncertainties, syntheses of these

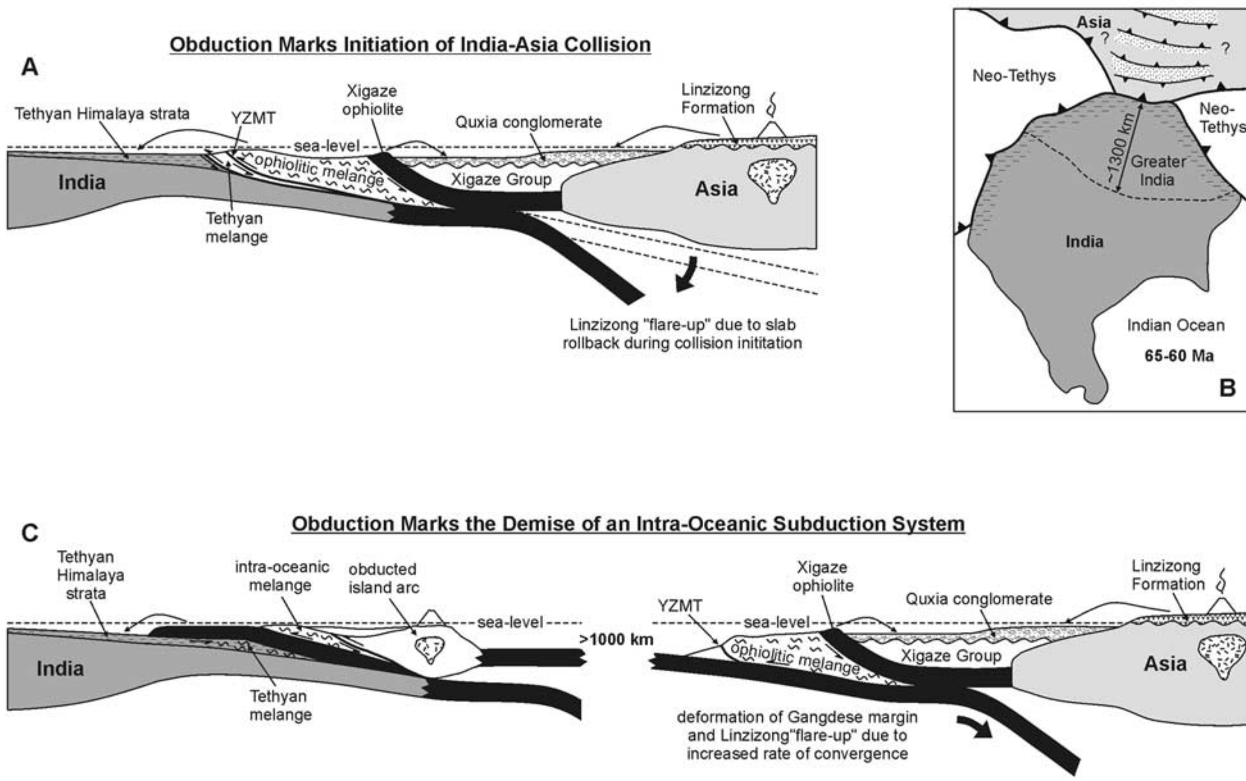

Figure 11. Two contrasting tectonic models that can explain southward obduction of oceanic rocks onto the northern margin of India during latest Cretaceous–earliest Tertiary time (~65 Ma) and coeval changes in sedimentation within the northern Tethyan Himalaya and Gangdese forearc. (a) Ophiolitic rocks were obducted southward onto the Indian margin from beneath the Gangdese forearc. The development of an angular unconformity in the Gangdese forearc and southern Lhasa terrane marks the initiation age of tectonic interaction between the Indian and Asian continental margins. Linzizong volcanism is related to rollback of a formerly shallow subducting Neo-Tethys oceanic slab in response to collision initiation. Arrows indicate sediment dispersal directions and sources. (b) Paleogeographic reconstruction in map view shows onset of collision between India and Asia in south central Tibet at ~65 Ma. Remnants of the Neo-Tethys Ocean may have remained to the west and east of south central Tibet. This hypothesis predicts major intracontinental shortening along and to the north of the Yarlung Zangbo suture during Paleocene time. (c) Ophiolitic fragments and a north dipping subduction-accretion complex and associated island arc were obducted southward onto the Indian margin >1000 km south of the southern Asian continental margin. Coeval development of an angular unconformity in the Gangdese forearc and southern Lhasa terrane and onset of Linzizong volcanism are related to an increase in the rate of ocean-continent convergence following demise of the intraoceanic subduction system to the south. Arrows indicate sediment dispersal directions and sources. The intraoceanic rocks obducted onto the Indian margin must have been underthrust along the Yarlung Zangbo suture subsequent to Eocene collision initiation to explain their apparent absence in south central Tibet.

results suggest initial contact between India and Asia at 65–60 Ma [*Klootwijk et al.*, 1992; *Patzelt et al.*, 1996]. An early age for collision initiation is also supported by the appearance of Asian terrestrial faunas in the Deccan Trap region of the southwestern India at ~65 Ma [*Jaeger et al.*, 1989].

[35] Early India-Asia collision predicts ~1400 km of intracontinental shortening between 65 and 55 Ma, considering an average convergence rate of ~14 cm/yr during this time interval [*Lee and Lawver*, 1995]. No Paleocene shortening has been documented in the Tethyan Himalaya, significantly challenging this hypothesis. However this geologic record could have been completely underthrust or subducted beneath the Lhasa terrane along the YZSZ [*Yin and Harrison*, 2000]. Alternatively, Paleocene shortening is not required in the Tethyan Himalaya if it was localized further to the north in Asia. While Paleocene shortening of the southern Lhasa terrane was minimal, it could have been substantial to the north on the basis of the wide distribution of Paleocene contraction-related nonmarine basins within and surrounding the Tibetan Plateau [e.g., *Burchfiel et al.*, 1995; *Yin and Harrison*, 2000; *Horton et al.*, 2002; *Kapp et al.*, 2005b]. Nevertheless, shortening of the magnitude

predicted by the early India-Asian collision model is not presently substantiated by existing geologic evidence.

6.4.2. Obduction Marks the Demise of an Intraoceanic Subduction System

[36] Oceanic rocks may have been obducted onto the northern margin of India as it entered an intraoceanic subduction zone located >1000 km south of Asia (Figure 11c) [e.g., *Gnos et al.*, 1997; *Makovsky et al.*, 1999; *Aitchison et al.*, 2000]. The demise of the intraoceanic subduction system would have resulted in an abrupt increase in the rate of ocean-continent convergence along the southern Asian margin. This in turn may have initiated shortening and uplift within the Gangdese subduction-accretion complex and forearc as well as voluminous Linzizong volcanism. Obducted ophiolites and Cretaceous arc fragments are apparently lacking along the YZSZ in south central Tibet. They could have been completely underthrust beneath the southern Asian margin during the India-Asia collision [*Makovsky et al.*, 1999]. Continental collision during the early or middle Eocene is consistent with current estimates for the history of shortening and foreland basin development within the central Himalaya [*DeCelles et al.*, 2002], a decrease in India-Asia convergence during this time [e.g., *Patriat and Achache*, 1984; *Besse and Courtillot*, 1988; *Dewey et al.*, 1989; *Klootwijk et al.*, 1992; *Lee and Lawver*, 1995], and the presence of Asian-derived detritus within sandstones from the upper Paleocene–middle Eocene Zheya Formation [this study].

[37] This model may be tentatively favored because it does not require major, but presently unaccounted for, Paleocene shortening in Asia. However, it does raise concern as to why ocean-continent convergent margin tectonism apparently produced more dramatic changes in sedimentation within the northern Tethyan Himalaya and Gangdese forearc than the subsequent initiation of collision between India and Asia. While a precise chronostratigraphy is lacking, our results strongly suggest the Zheya Formation of the northern Tethyan Himalaya provides a newly discovered stratigraphic record of India-Asia collision initiation. We speculate that its future study will help address the above concern as well provide unprecedented constraints on the timing of India-Asia collision in south central Tibet.

7. Conclusions

[38] Northern Tethyan Himalaya strata of the northern Indian margin are characterized by a transition from shallow to deep marine sedimentation between ~68 and 65 Ma and an appearance of detrital spinel of ophiolite affinity during the Paleocene. To the north, the Yarlung Zangbo Mantle thrust shear places ophiolitic melange in the hanging wall southward over a sedimentary-matrix melange which includes blocks of Tethyan strata. Cooling of a mafic schist within the shear zone at ~63 Ma is attributed to shear zone movement and southward obduction of the ophiolitic melange at this time. These results provide new evidence for initial southward obduction of oceanic rocks onto the northern margin of India during latest Cretaceous–earliest Tertiary time. Paleocene-Eocene marine strata of the Gangdese forearc lie above an angular unconformity which developed between late Maastrichtian time and ~62 Ma and also include detrital clasts of ophiolite affinity spinel. Geochronologic detrital mica and zircon provenance studies suggest an input of Asian-affinity detritus into northern Tethyan Himalaya strata by Lutetian time, providing a robust minimum estimate for the initiation age of India-Asia collision in south central Tibet. Pelitic schist locally underlies northern Tethyan Himalaya Paleozoic strata in the core of an anticline. The schist is intruded by an undeformed ~45 Ma leucogranite and yields a $^{40}Ar/^{39}Ar$ muscovite age of ~41 Ma. Crustal anatexis and cooling is attributed to crustal thickening following initiation of shortening within the northern Tethyan thrust belt. Our results are compatible with southward obduction of ophiolitic rocks onto the northern Indian margin at ~65 Ma marking either (1) onset of tectonic interaction between India and Asia at this time or (2) the demise of a Neo-Tethys intraoceanic subduction system followed by initial India-Asia contact during late Paleocene to middle Miocene time. Future studies of the newly documented northern Tethyan Himalaya strata have unique potential to distinguish between these models and precisely constrain the initiation age of India-Asia collision in south central Tibet.

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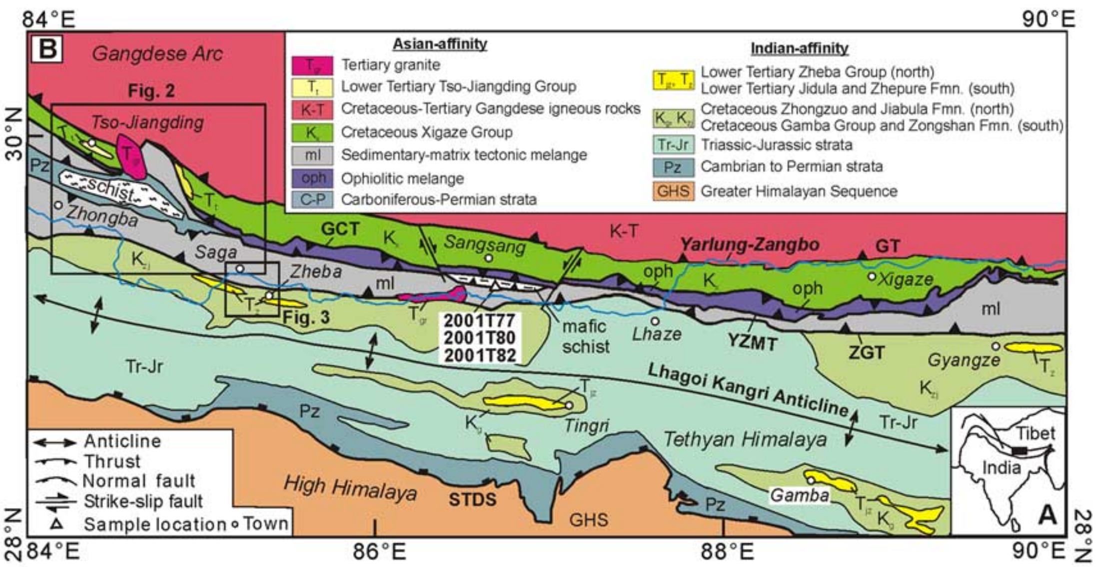

Figure 1. (a) Inset map shows location of study area in south central Tibet. (b) Simplified geologic map of south central Tibet based on *Liu* [1988] and our own observations. Additional significant fold-thrust belt structures occur within the Tethyan Himalaya but are not shown here for clarity. Abbreviations are as follows: GCT, Great Counter thrust; GT, Gangdese thrust; STDS, south Tibetan detachment system; YZMT, Yarlung Zangbo Mantle thrust; ZGT, Zhongba-Gyangze thrust.

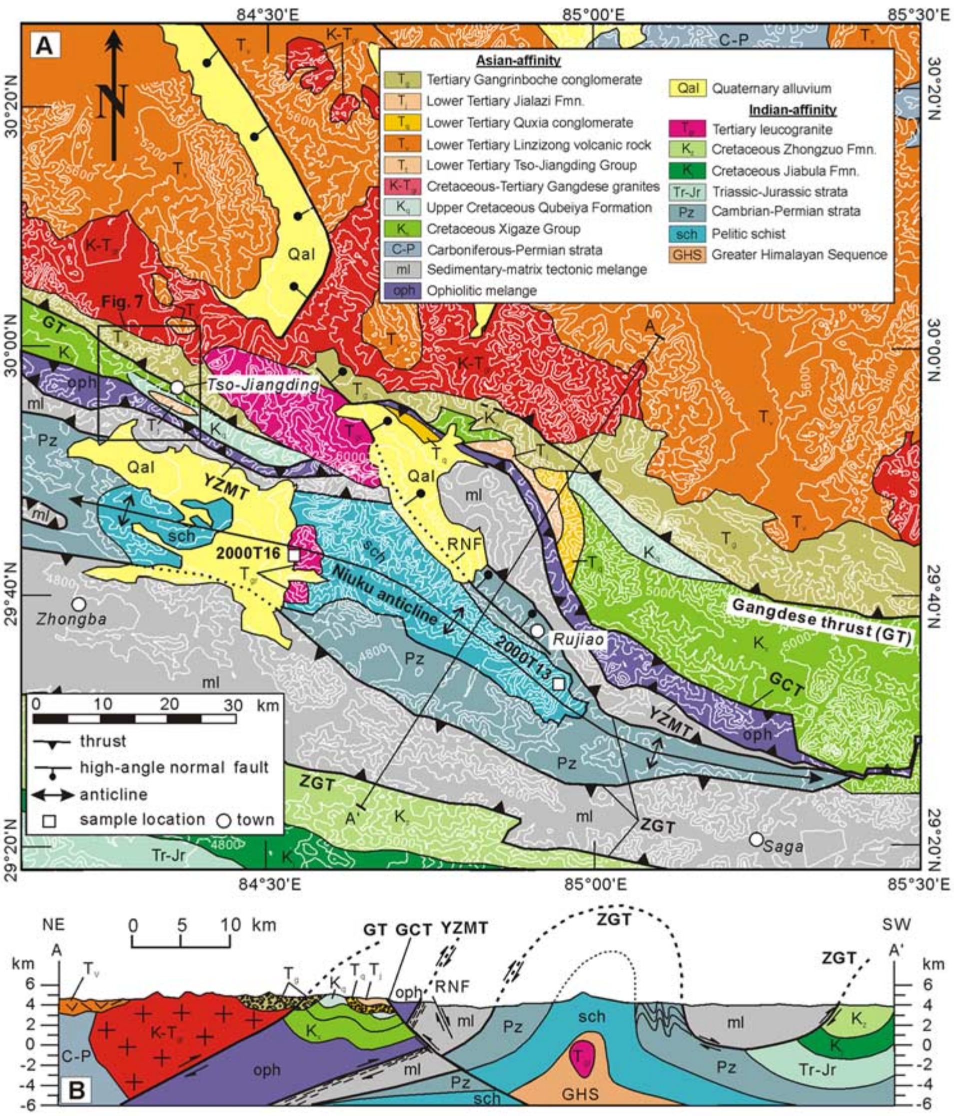

Figure 2. (a) Geologic map of the Yarlung Zangbo suture zone in south central Tibet. (b) Schematic cross section along line A-A′ shown in Figure 2a. Fault abbreviations are as follows: GCT, Great Counter thrust; GT, Gangdese thrust; RNF, Rujiao normal fault; YZMT, Yarlung Zangbo Mantle thrust; ZGT, Zhongba-Gyangze thrust.

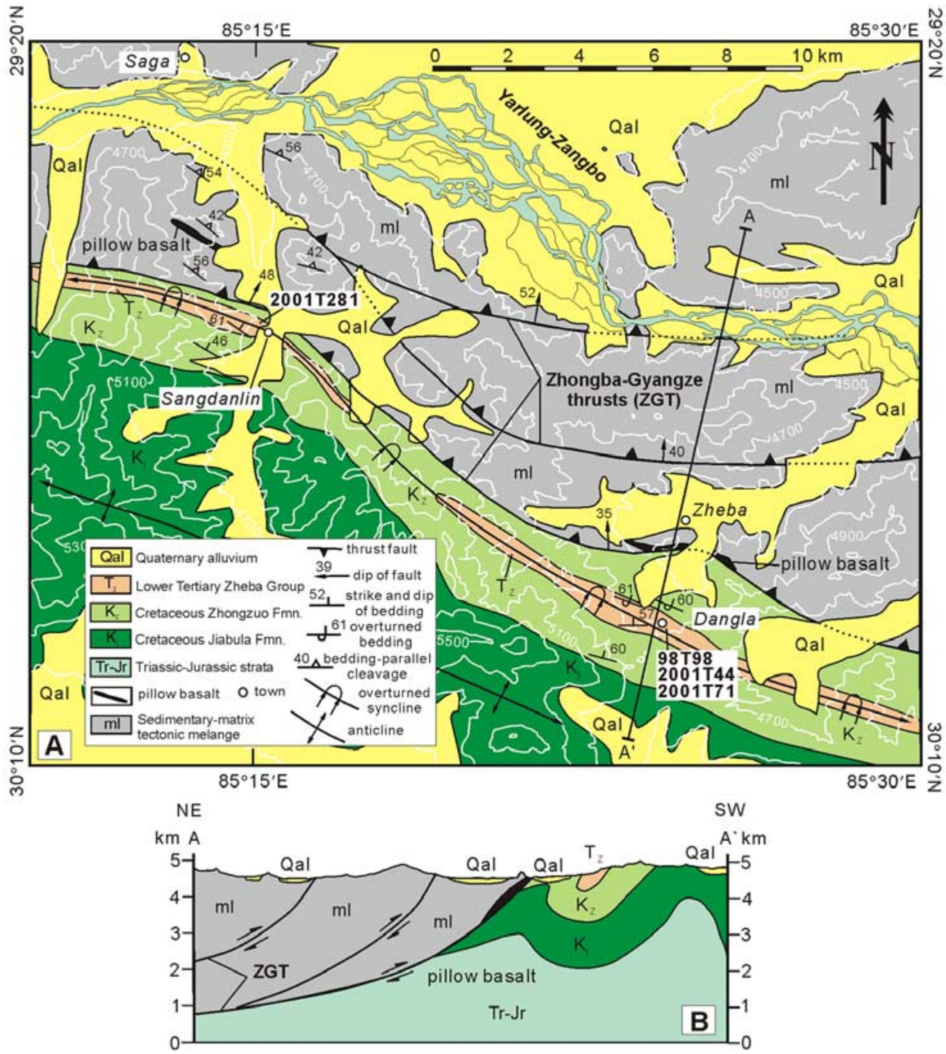

Figure 3. (a) Geologic map of the Sanganlin-Dangla area in the northern Tethyan Himalaya. (b) Schematic cross section across line A-A′ shown in Figure 3a. Fault abbreviation is ZGT, Zhongba-Gyangze thrust.

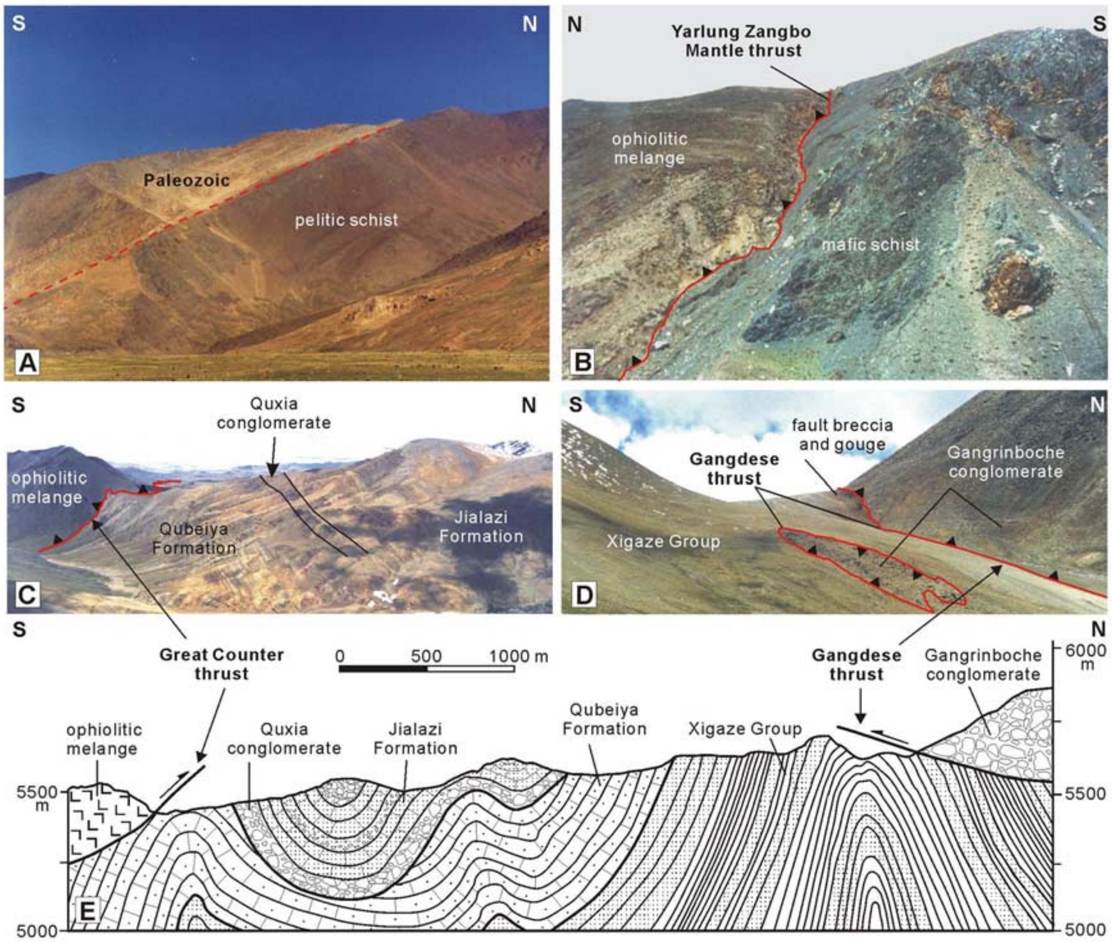

Figure 4. (a) View of the southern limb of the Niuku antiform looking toward the west. Here Paleozoic metasandstone and metalimestone overlie pelitic schist. The sample dated in this study (2000T13) was collected from this exposure in the Rujiao area (Figure 2). (b) View of the north dipping Yarlung Zangbo Mantle thrust looking toward the east in the Sangsang area (Figure 1). The thrust juxtaposes ophiolitic melange in the hanging wall against a fault zone sliver of amphibole-bearing mafic schist in the footwall. Samples 2001T77, 2001T80, and 2001T82 were collected from this outcrop (Figure 1). (c) View toward the west of the south dipping Great Counter thrust in the Tso-Jiangding area (Figure 7), with ophiolitic melange in the hanging wall and the lower Tertiary Qubeiya Formation, Quxia conglomerate, and Jialazi Formation in the footwall. (d) View of the Gangdese thrust looking toward the west in the Tso-Jiangding area. The Gangdese thrust juxtaposes the Gangrinboche conglomerate in the hanging wall against the Xigaze Group in the footwall. (e) Cross section showing the major structures in the Tso-Jiangding area, including the angular unconformity beneath the Quxia conglomerate.

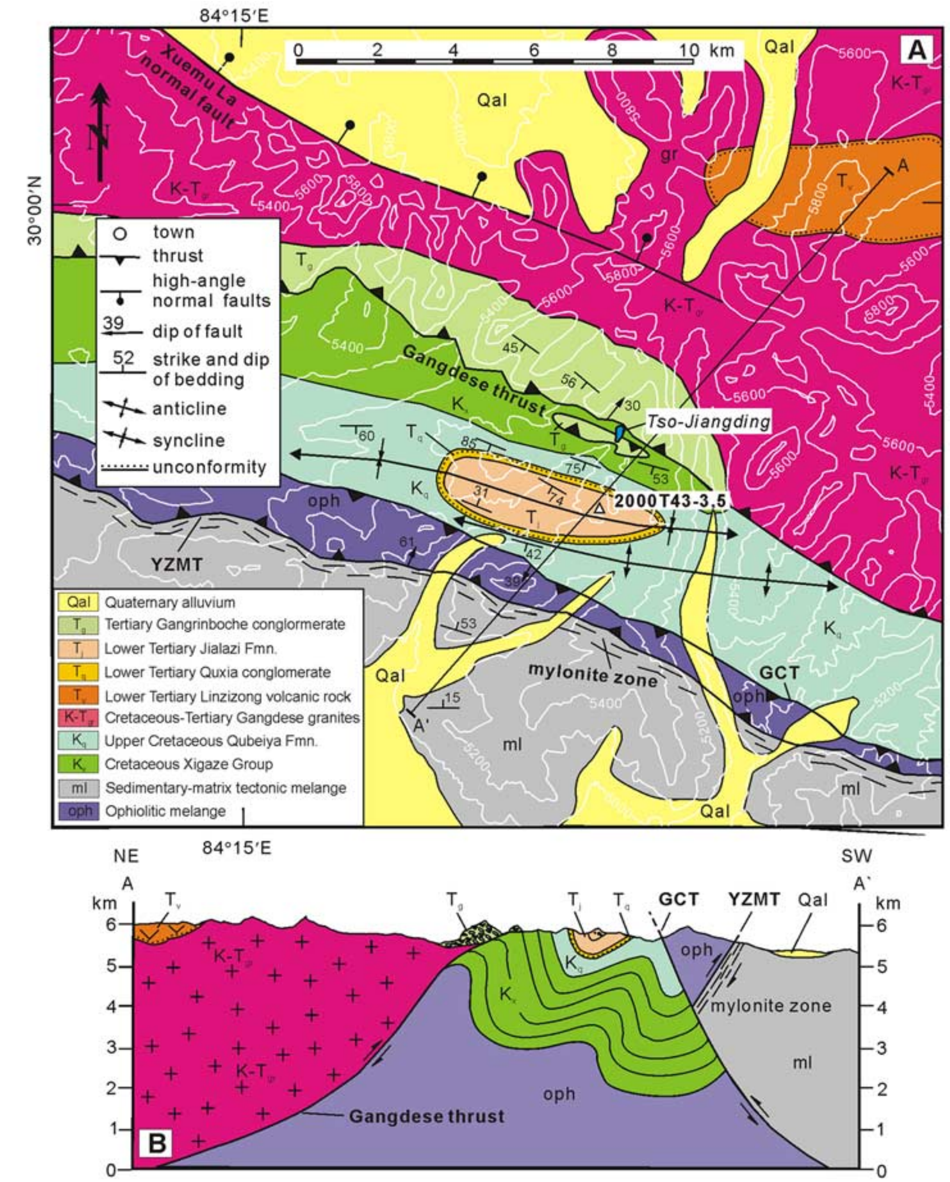

Figure 7. (a) Geologic map of Tso-Jiangding area in southern Tibet. (b) Schematic cross section along line A-A′ shown in Figure 7a. Fault abbreviations are as follows: GCT, Great Counter thrust; YZMT, Yarlung Zangbo Mantle thrust.