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Key Points:

- Semicontinuous suture zone record of Asian convergent margin development and India-Asia collision since Jurassic time
- No evidence for arc-continent collision or multiple subduction zones south of the fore arc since circa 97 Ma
- Deformation, metamorphism, and magmatism are consistent with a model involving episodes of underthrusting, rollback, and slab breakoff

Supporting Information:

- Supporting Information S1

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Tectonic evolution of the Yarlung suture zone, Lopu Range region, southern Tibet

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Abstract The Lopu Range, located ~600 km west of Lhasa, exposes a continental high-pressure metamorphic complex beneath India-Asia (Yarlung) suture zone assemblages. Geologic mapping, 14 detrital U-Pb zircon ($n = 1895$ ages), 11 igneous U-Pb zircon, and nine zircon (U-Th)/He samples reveal the structure, age, provenance, and time-temperature histories of Lopu Range rocks. A hornblende-plagioclase-epidote paragneiss block in ophiolitic mélange, deposited during Middle Jurassic time, records Late Jurassic or Early Cretaceous subduction initiation followed by Early Cretaceous fore-arc extension. A depositional contact between fore-arc strata (maximum depositional age 97 ± 1 Ma) and ophiolitic mélange indicates that the ophiolites were in a suprasubduction zone position prior to Late Cretaceous time. Five Gangdese arc granitoids that intrude subduction-accretion mélange yield U-Pb ages between 49 and 37 Ma, recording Eocene southward trench migration after collision initiation. The south dipping Great Counter Thrust system cuts older suture zone structures, placing fore-arc strata on the Kailas Formation, and sedimentary-matrix mélange on fore-arc strata during early Miocene time. The north-south, range-bounding Lopukangri and Rujiao faults comprise a horst that cuts the Great Counter Thrust system, recording the early Miocene (~16 Ma) transition from north-south contraction to orogen-parallel (E-W) extension. Five early Miocene (17–15 Ma) U-Pb ages from leucogranite dikes and plutons record crustal melting during extension onset. Seven zircon (U-Th)/He ages from the horst block record 12–6 Ma tectonic exhumation. Jurassic–Eocene Yarlung suture zone tectonics, characterized by alternating episodes of contraction and extension, can be explained by cycles of slab rollback, breakoff, and shallow underthrusting—suggesting that subduction dynamics controlled deformation.

1. Introduction

Intercontinental suturing is a fundamental process in the amalgamation of Earth's supercontinents, growth and recycling of continental crust, and creation of collisional orogenic belts [Burke *et al.*, 1977; Moores, 1981; Clift *et al.*, 2009]. The geologic evolution of suture zones also provides insights about the dynamics of intercontinental collisions. The Yarlung suture zone, located along the Yarlung River valley (Figures 1 and 2), and the Indus suture zone, located along the Indus River valley (Figure 1), comprise the Indus-Yarlung (India-Asia) suture (Figures 1 and 2). The Yarlung suture zone segment in southern Tibet (Figure 2) is both geographically and geologically central to the Himalayan-Tibetan system, which is the most prominent Cenozoic collisional orogen. Nevertheless, it is insufficiently understood—permitting a wide range of tectonic models. Collision initiation age estimates between 70 and 25 Ma [e.g., Yin and Harrison, 2000; Aitchison *et al.*, 2007; van Hinsbergen *et al.*, 2012] illustrate this variance. This study seeks to better understand the evolution of the Yarlung suture zone before and during continental collisional orogenesis by investigating the Lopu Range, located ~600 km west of Lhasa city in south central Tibet (Figures 1 and 2). This ~100 km by 50 km NW-SE trending mountain range achieved its high relief during Miocene-recent orogen-parallel extension [Taylor and Yin, 2009; Sanchez *et al.*, 2013] and exposes a >1.5 km thick panel of suture zone architecture.

Uncertainties surrounding the precollisional configuration of the Asian margin, the age(s) of collision(s), the genesis of continental high-pressure (HP) metamorphic complexes along the Indus-Yarlung suture, the response of the Asian convergent margin magmatic arc to collision, and the role of younger fault systems that cut the suture prevent formulation of a comprehensive tectonic model. In this study, we present new geologic mapping, structural analysis, detrital and igneous U-Pb zircon geochronology, and zircon (U-Th)/He thermochronology from the Lopu Range to address these issues. First, we investigate the contact and age relationships between ophiolitic rocks and the Xigaze fore-arc basin to determine whether the ophiolite formed proximal to the Lhasa terrane or in an intraoceanic arc setting. Second, we determine the age and provenance of

Figure 1. Geographic and geologic features of the Tibetan Plateau, Himalayas, and northwestern Himalaya. Active structures were adapted from Taylor and Yin [2009]. Basemap is a digital elevation model from the Global Multi-Resolution Topography (GMRT) Synthesis [Ryan et al., 2009] rendered in GeoMapApp (<http://www.geomapapp.org>).

Figure 2. Tectonic map and cross section of southern Tibet and the Himalaya modified from Orme et al. [2015, and references therein]. Faults within the Tethyan Himalaya Sequence, Lesser Himalaya Sequence, and Lhasa terrane are not shown on the tectonic map but are schematically illustrated in cross section. Miocene-recent normal faults are also omitted but are shown in Figure 1. GCT = Great Counter Thrust system; NHD = North Himalayan domes; STDS = South Tibetan Detachment System; MCT = Main Central Thrust; and MBT = Main Boundary Thrust.

metasedimentary rocks in the Lopu Range. Third, we document the magmatic record of convergence along the southern margin of Asia and the response of the arc to intercontinental collision. Finally, we investigate the geologic record of the switch from upper crustal N-S shortening to E-W extension during Miocene time. Integration of geologic records from the Lopu Range with regional studies demonstrates that episodes of deformation, metamorphism, and magmatism along the Yarlung suture can be explained by episodes of underthrusting, rollback, and breakoff of subducting oceanic and continental lithosphere. Therefore, we propose that subduction dynamics governed the assembly of the Asian convergent margin and the response of Indian and Asian crust to intercontinental collision throughout late Mesozoic-Cenozoic time.

2. Regional Geologic Background

The Yarlung suture, demarcated by ophiolitic rocks and subduction-accretion mélanges, divides Paleozoic-Mesozoic Lhasa terrane (Asian convergent margin) and northern Tethyan Himalaya (Indian passive margin) rocks in southern Tibet. From north to south, major rock units of the southern margin of Asia include Cretaceous-Paleogene calc-alkaline rocks of the Gangdese batholith [Schärer *et al.*, 1984] and dominantly Paleocene-Eocene volcanic and volcanoclastic rocks (the Linzizong Formation) [Lee *et al.*, 2009], Oligo-Miocene nonmarine strata of the Kailas (Gangrinboche) Formation [Gansser, 1964; Aitchison *et al.*, 2002; DeCelles *et al.*, 2011; Leary *et al.*, 2016], and Cretaceous marine and Paleogene marine and nonmarine strata of the Xigaze (Gangdese) fore-arc basin [Einsele *et al.*, 1994; Dürr, 1996; Wang *et al.*, 2012; An *et al.*, 2014; Orme *et al.*, 2015; Orme and Laskowski, 2016] (Figures 1 and 2). The Kailas Formation consists of alluvial-fan conglomerate, fluvial sandstone, and deep lacustrine shale deposited in buttress unconformity with exhumed Gangdese arc rocks. Fore-arc strata consist of sandstone, shale, conglomerate, and limestone that record a shoaling upward sequence during the Cretaceous-Paleocene.

Ophiolitic fragments along the Yarlung suture between Mount Kailas and Xigaze (Figure 1) formed at 132–122 Ma [Hébert *et al.*, 2012; Chan *et al.*, 2015] and are interpreted to have been obducted onto the Indian margin during Cretaceous-Paleogene time [Burg and Chen, 1984; Girardeau *et al.*, 1984; Searle *et al.*, 1987; Malpas *et al.*, 2003; Ding *et al.*, 2005; Guilmotte *et al.*, 2009] or as late as Eocene time [Davis *et al.*, 2002]. Cai *et al.* [2012] argue on the basis of detrital zircon geochronology and structural relationships that the ophiolitic fragments were located along the southern margin of Asia during the Cretaceous. Other studies favor ophiolite formation in an extensional fore-arc setting proximal to the southern Lhasa terrane, above which the Xigaze Group was deposited [Hébert *et al.*, 2012; Wang *et al.*, 2012; An *et al.*, 2014; Orme *et al.*, 2015; Huang *et al.*, 2015; Maffione *et al.*, 2015; Orme and Laskowski, 2016]. A belt of sedimentary-matrix mélange is exposed south of the ophiolitic fragments. These rocks likely formed in an accretionary wedge setting structurally below the ophiolite [Burg *et al.*, 1987; Einsele *et al.*, 1994; Cai *et al.*, 2012].

Indian passive margin strata of the Tethyan Himalaya sequence [e.g., Gaetani and Garzanti, 1991; Liu and Einsele, 1994; Garzanti, 1999] are exposed to the south of the sedimentary-matrix mélange and range in age from Cambrian-Eocene. In southeastern Tibet, Tethyan Himalaya sequence rocks reached peak greenschist-amphibolite facies conditions circa 44 Ma due to shortening in the Tethyan fold-thrust belt [Dunkl *et al.*, 2011] (Figures 1 and 2). High- to ultrahigh-pressure Tethyan Himalaya sequence rocks in the northwest Himalaya (Tso Moriri and Kaghan complexes, Figure 1) experienced ultrahigh-pressure metamorphism and rapid exhumation during Eocene time [Guillot *et al.*, 2008; Kohn, 2014]. The Tethyan Himalaya physiographic zone is disturbed by a belt of structural culminations—the north Himalayan domes (Figures 1 and 2)—which expose Neoproterozoic amphibolite- and higher-grade metasedimentary rocks of the Greater Himalayan sequence (GHS) [e.g., Burg *et al.*, 1984; Lee *et al.*, 2004] in their footwalls. Greater Himalayan metasedimentary rocks are intruded by 550–400 Ma plutons and likely sourced a large component of the overlying Tethyan Himalaya passive margin sequence [DeCelles *et al.*, 2000; Gehrels *et al.*, 2011]. The southern limit of the Tethyan Himalayan zone is defined by the north dipping South Tibetan Detachment System (STDS) [Burchfiel *et al.*, 1992; Hodges *et al.*, 1996], with Greater Himalayan rocks in the footwall (Figure 2).

Primary Yarlung suture structures are obscured by the south dipping, north directed Great Counter Thrust system (GCT) [Heim and Gansser, 1939], juxtaposing Tethyan Himalaya sequence rocks against suture zone mélange and ophiolite, mélange and ophiolite against fore-arc strata, and fore-arc strata against the Kailas Formation (Figures 1 and 2). The Great Counter Thrust system comprises one or more moderately to steeply

south dipping reverse faults along strike in southern Tibet [e.g., Zhang *et al.*, 2011; Laskowski *et al.*, 2016], corresponding to the presence or absence of suture zone rock units between the Kailas Formation and the Tethyan Himalaya sequence. The Great Counter Thrust system was active during the early to mid-Miocene based on crosscutting relationships, and its slip magnitude is poorly constrained because of a lack of hanging wall cutoffs [Ratschbacher *et al.*, 1994; Quidelleur *et al.*, 1997; Yin *et al.*, 1999].

Radiogenic heating, shear heating, and/or isothermal decompression generated abundant crustal melts in southern Tibet and the Himalayas [Le Fort, 1975; England and Thompson, 1984; Harris and Massey, 1994; Harrison *et al.*, 1998]. Approximately 23–15 Ma High-Himalayan leucogranites [Schärer *et al.*, 1986; Noble and Searle, 1995; Harrison *et al.*, 1997b; Searle *et al.*, 1997; Searle and Godin, 2003] intrude Greater Himalayan sequence rocks in the footwall of the South Tibetan Detachment System [Le Fort, 1986; Searle, 1999]. Approximately 35–9 Ma North Himalayan leucogranites [Schärer *et al.*, 1986; Harrison *et al.*, 1997a; Zhang *et al.*, 2004; Larson *et al.*, 2010; Liu *et al.*, 2016] are exposed in the cores of North Himalayan domes [e.g., Lee *et al.*, 2004] and locally within the Yarlung suture zone (Figures 1 and 2). Eocene (~45–40 Ma) leucogranites that intrude the Tethyan Himalaya sequence suggest significant crustal thickening in the Himalayan-Tibetan orogenic belt [Ding *et al.*, 2005; Aikman *et al.*, 2008; Pullen *et al.*, 2011].

Arc-parallel extension, which initiated between 17 and 14 Ma [e.g., Garzione *et al.*, 2003; Murphy and Copeland, 2005; Thiede *et al.*, 2006; Hintersberger *et al.*, 2010; McCallister *et al.*, 2014; Styron *et al.*, 2015], is the dominant structural mode affecting the upper crust of the southern Tibetan Plateau. In south central Tibet, approximately N-S striking normal faults cut the Yarlung suture and the South Tibetan Detachment System and have locally exhumed rocks from beneath the brittle-ductile transition in their footwalls [e.g., Kapp *et al.*, 2008; Taylor and Yin, 2009] (Figures 1 and 2).

3. Geographic Setting

This study focuses on an ~2500 km² map area surrounding the Lopu Range (Figures 1 and 2). The southern tip of the range is located ~40 km northwest of Saga, in Xizang (Tibetan Autonomous Region), China (Figure 1). The Lopu Range is more than 100 km long, northwest-southeast oriented, and is crowned by Lopu Kangri (sometimes referred to as Loinbo Kangri or Lopukangri) at an elevation of 7095 m. The Gangdese Mountains (referred to as the Kailas Range or Transhimalaya; Figure 1) intersect the Lopu Range. The central Lopu Range averages >6000 m in elevation and is glaciated, with thick moraine deposits that extend to ~5800 m above sea level along the eastern flank.

The approximately E-W trending Gangdese Mountains define the southern limit of internal drainage on the Tibetan Plateau (Figure 1). To the west of Lopu Kangri, the range assumes a northwest-southeast orientation that mimics the trend of the Himalayas along the China-Nepal border (Figure 1). Sumje Pass summits the intrabasin high on the east flank of Lopu Kangri (Figure 3). Glaciers and outwash along the northeast flank of Lopu Kangri feed the Bultok River, which flows north to Taro Lake. Glaciers and outwash along the south side of Lopu Kangri feed the Men Chu River, which discharges into the Yarlung River at Saga, and a tributary of unknown name, which discharges into the Yarlung River ~140 km to the west in the town of Zhongba.

4. Structural Geology

Geologic mapping (Figure 3) was conducted at 1:50,000 scale, drafted at 1:125,000 atop Landsat imagery and topographic contours (100 m interval) generated from 3 arc sec Shuttle Radar Topography Mission data, and resized to ~1:250,000 for inclusion in this paper. Dashed contacts in the interior of the range were traced in Google Earth, as extreme elevation (>6000 m) and snow/ice cover prohibited access.

4.1. Map Units

The northernmost rocks in the Lopu Range region are Gangdese arc granitoids that were mapped as two units based on their age and composition. Paleogene phaneritic granodiorites (Pgg) are exposed along the high peaks of the Gangdese Shan, including Lopu Kangri (Figure 3). Neogene two-mica leucogranite dikes, sills, and plutons (Ng) intrude meta-Tethyan rocks, Gangdese arc rocks, and sedimentary-matrix mélange.

Cobble to pebble conglomerate was deposited in buttress unconformity with Gangdese arc rocks [Sanchez *et al.*, 2013] and is exposed in the footwall of the Great Counter Thrust system in the Lopu Range region.

Figure 3. Approximately 1:250,000 scale geologic map of the Lopu Range. Overlapping structural measurements of similar orientation were averaged for clarity. Six structural measurements and the Great Counter Thrust and Lopukangri fault contact traces on the west side of the range were adapted from *Sanchez et al.* [2013]. Cross section lines A-A' and B-B' refer to Figure 5. Average zircon (U-Th)/He and U-Pb ages and their associated uncertainties were rounded to the nearest whole number.

This locally >2.5 km thick unit transitions from volcanic and plutonic clast dominance to sedimentary clast dominance from bottom to top [Sanchez et al., 2013]. Sedimentary petrography and a lack of lacustrine interval led Sanchez et al. [2013] to correlate these rocks to the Eocene-Oligocene Qiuwu Formation. Following the classification scheme of Aitchison et al. [2002], we group this unit with the Oligocene-Miocene Kailas Formation (OMk, also called Gangrinboche conglomerates), which is a ~1300 km long belt of fluvial-alluvial-lacustrine strata that were deposited in buttress unconformity atop Gangdese arc rocks, exposed in the footwall of the Great Counter Thrust system [e.g., DeCelles et al., 2011; Leary et al., 2016]. We interpret that the lack of a lacustrine interval is a local feature of the Kailas Formation in the Lopu Range region.

Cretaceous to Eocene Xigaze fore-arc basin strata (KEx) are exposed south of Kailas Formation strata on both the eastern and western sides of the Lopu Range (Figure 3), comprising a >4.5 km shoaling upward sequence of sandstone, conglomerate, and sandy limestone [Orme et al., 2015]. Fore-arc strata are folded across a broad, ~15 km wide syncline just east of the map area; only the northern limb is exposed near the Lopu Range (Figure 3). Farther south, fore-arc strata are in fault contact with a unit of sedimentary-matrix mélangé (mlg),

which consists of centimeter- to kilometer-scale blocks of shale, chert, metabasalt, basalt, limestone, quartzite, phyllite, conglomerate, and minor volcanic rocks in a strongly deformed shale and sandstone matrix. The Lopu Range horst block exposes conglomerate blocks within sedimentary-matrix *mélange* between the late Cenozoic to recently active [Ding *et al.*, 2005; Sanchez *et al.*, 2013] Lopukangri and Rujiao normal faults (Figure 3). In the northeast, ophiolitic *mélange* (oph) is exposed between the Xigaze fore arc and the sedimentary-matrix *mélange* (Figure 3), consisting of gabbro and serpentinite blocks up to ~3 m in diameter separated by centimeter-scale shear zones.

Sedimentary-matrix *mélange* is folded across the ESE trending, gently plunging Niuku anticline [Ding *et al.*, 2005], cored by three units of metasedimentary rocks with Indian protoliths. The Indian metasedimentary rocks were distinguished as map units based on their age, detrital zircon U-Pb age spectra, metamorphic grade, and composition (Figure 3). To the west of the Lopu Range, the core of the anticline is composed of organic-rich, blue-gray phyllite (unit Pp) with local fossiliferous limestone beds indicating a Permian age [Hebei Province Geologic Survey, 2002]. Pyrite cubes up to ~1 cm in diameter and abundant sheared, folded, and/or boudinaged quartz-mica veins are present in the phyllite. Schist, calc-paragneiss, paragneiss, and quartzite with detrital zircon age spectra typical of the Tethyan Himalaya sequence (COg) and tectonically interleaved quartzite and quartz-rich paragneiss with distinct detrital zircon age spectra (Zq) compose the anticline core in the Lopu Range horst block (Figure 3). Detrital zircon age spectra indicate a Cambrian to Ordovician age for unit COg, which we correlate with the Tethyan Himalaya sequence. We present two possible correlations for unit Zq, characterized by distinct detrital zircon age spectra with Neoproterozoic maximum depositional ages (see section 7.1).

4.2. Fault Systems

4.2.1. Yarlung-Zangbo Mantle Thrust

The Yarlung-Zangbo mantle thrust (YZMT) is the oldest structure in the Lopu Range region and places hanging wall ophiolitic *mélange* atop footwall sedimentary-matrix *mélange* across a ~50° north dipping, reverse-sense mylonitic shear zone (Figure 3). The YZMT bounds the southern exposure of ophiolitic *mélange* at all locations in the map area and is faulted out to the east of the Lopu Range by a strand of the Great Counter Thrust system (Figure 3). Amphibole $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of ~63 Ma from a mafic schist in the shear zone, ~200 km along strike to the east, are interpreted to record exhumation-related cooling during slip and southward emplacement of ophiolitic *mélange* on accretionary wedge rocks [Ding *et al.*, 2005].

4.2.2. Dajiling Fault

The Dajiling fault is a >2 km thick zone of protomylonite and mylonite folded across the Niuku Anticline (Figures 3 and 4c) and exposed in the central and southern Lopu Range [Laskowski *et al.*, 2016]. On the north limb of the anticline, it strikes E-W, dips ~60°N, and juxtaposes low-grade sedimentary-matrix *mélange* in the hanging wall against footwall meta-Tethyan calc-paragneiss and mesoscale to macroscale quartzite and quartz-rich paragneiss lenses (Figure 4c). On the south side of the Niuku Anticline, the Dajiling fault is south dipping and juxtaposes Tethyan phyllite (Pp) in the hanging wall against footwall paragneiss, quartzite, and schist (units COg and Zq). S-C fabrics and asymmetric porphyroclasts indicate top-to-the-north shear along both the northern and southern exposures (Figure 4d). The juxtaposition of high-grade footwall rocks with low-grade hanging wall rocks across the Dajiling fault and the uniform, top-to-the-north sense-of-shear across it suggest that this structure accommodated exhumation of footwall rocks.

Farther south, a poorly exposed, south dipping fault with unknown kinematics juxtaposes phyllite (Pp) in the footwall against hanging wall sedimentary-matrix *mélange* (mlg). The presence of the phyllite in the hanging wall of the southern exposure of the Dajiling fault can be explained by interpreting a fault branching from the Dajiling fault at a structurally high, now eroded location above the Niuku anticline (B-B', Figure 5). To the west of the Lopu Range, no high-grade meta-Tethyan rocks are exposed in the hanging wall of the Lopukangri fault. Instead, the phyllite thrust sheet is exposed at the center of the Niuku anticline. The shallower structural level exposed in the hanging wall of the Lopukangri fault relative to the footwall can explain this geometry (A-A', Figure 5).

4.2.3. Great Counter Thrust

The northernmost strand of the 25–68° south-southwest dipping Great Counter Thrust system (GCT; Figures 3, 5, and 6b) places Xigaze fore-arc strata (KEx) in the hanging wall on 23–57° south dipping [Sanchez *et al.*, 2013; this study] Kailas Formation (OMk) in the footwall to the west and east of the Lopu

Figure 4. Outcrop and landscape photos. Photo locations are plotted in Figure 3. (a) Thrust sheet with quartzite (unit Zq, Figure 3) and overlying meta-Tethyan rocks in the hanging wall in the southern Lopu Range (photo looking NW). (b) Depositional contact between Xigaze fore-arc basin strata (samples 71314AL3-4) and overlying ophiolitic mélangé. (c) The northern exposure of the Dajiling fault along the eastern Lopu Range front. Height of faceted fault zone exposure is ~20 m. (d) Asymmetric porphyroclasts, s-c fabrics and boudinaged quartz veins in Cambrian paragneiss (COg) within the southern exposure of the Dajiling fault, indicating top-to-the-north sense of shear. Hand drawn scale bar is ~3 cm. (e) View to the north of the triangular faceted Rujiao normal fault with Cambrian-Ordovician paragneiss and schist in the footwall and glacial moraine alluvium in the hanging wall.

Range. Kailas Formation strata are weakly deformed and metamorphosed but locally exhibit subgreenschist facies metamorphism and protomylonitic fabrics within ~50 m of the fault. Mineral elongation lineations in cataclasite and striated fault surfaces along the GCT indicate dip-slip motion (Figure 6b). Tectonic slivers (generally ~10 m thick and 20–50 m wide) of ophiolitic mélangé and amphibolite facies paragneiss are locally exposed along the northernmost strand (Figure 3); one sliver hosts blocks of banded hornblende-plagioclase-epidote paragneiss. Another strand of the GCT is exposed to the south, which juxtaposes hanging wall sedimentary-matrix and ophiolitic mélangé northward against Xigaze fore-arc strata. At the deeper structural level exposed in the Lopu Range horst block, the GCT consists of one south dipping fault that juxtaposes

Figure 5. Cross sections A-A' and B-B' keyed to the geologic map in Figure 3. Sample numbers for analytical data are plotted in Figure 3. Average Zircon (U-Th)/He and U-Pb ages and their associated uncertainties were rounded to the nearest whole number. Cross section B-B' is supplemented with sequentially restored sections based on our structural interpretations and timing constraints discussed in the text. YZMT = Yarlung-Zangbo Mantle thrust, GCT = Great Counter Thrust system, THS = Tethyan Himalaya sequence. Subsurface interpretations indicated by dashed contacts.

sedimentary-matrix mélangé (mlg) in the hanging wall against Gangdese batholith rocks (Pgg) in the footwall, implying that the strands exposed at higher structural levels merge at depth (Figures 3 and 5).

4.2.4. Lopukangri and Rujiao Faults

The Lopukangri and Rujiao normal faults [Ding et al., 2005; Murphy et al., 2010; Sanchez et al., 2013], exposed along the west and northeast sides of the Lopu Range (Figure 3), cut the YZMT, Dajiling fault, and GCT and are therefore the youngest faults in the region. Prominent triangular facets and 10–15 m fault scarps in glacial moraine deposits indicate Quaternary displacement (Figures 3 and 4e). The Lopukangri fault dips 45–50° to the west and juxtaposes low-grade, hanging wall sedimentary-matrix mélangé and phyllite against higher-grade, footwall sedimentary-matrix mélangé, Neogene leucogranite, and meta-Tethyan rocks from north to south. The NNW-SSE striking Rujiao fault dips 60–65° northeast along the southeast Lopu Range front, decreasing northwestward to ~45° northeast to the east of Lopu Kangri, and as low as ~20° northeast along the northeast range front (Figures 3 and 6c). The hanging wall of the Rujiao fault is composed of Xigaze

Figure 6. Structural data from (a) Indian metasedimentary rocks (COg and Zq), (b) the Great Counter Thrust (GCT), and (c) Rujiao fault on lower hemisphere equal area stereonets. In stereonet A, foliation is plotted as 1% area contours of poles. Cylindrical best fits are indicated by the squares.

fore-arc strata, sedimentary-matrix mélangé, and Tethyan phyllite from northwest to southeast. Striated fault surfaces developed in cataclasite and stretching lineations in structurally lower mylonites indicate top-down-to-the-east (average trend $\sim 86^\circ$), right-lateral, oblique normal displacement (Figures 3 and 6c).

5. Deformation and Metamorphism

5.1. Fabric Analysis

Deformation fabrics, including foliation, crenulation cleavage, S-C fabrics, mineral elongation lineations, and crenulation cleavage lineations, were measured at 167 locations within the Lopu Range (Figure 6). The most prominent fabric developed in high-grade meta-Tethyan rocks (COg) is schistose and gneissic foliation, which strikes NW-SE with a cylindrical best fit fold axis of 3° , 124° (Figure 6a), similar to the average orientation of the Rujiao fault (137° , 45° NE; Figure 6c). West of the Lopu Range, foliation strikes approximately E-W, parallel to the strike of the Dajiling fault (Figure 3). A prominent crenulation cleavage in schistose foliation indicates the presence of at least one previous generation of foliation. A generally N-S oriented stretching lineation accompanies foliation in Indian paragneiss and quartzite, yielding a cylindrical best fit fold axis of 10° , 086° (Figure 6a). These data lead us to interpret that the macroscopic foliation and stretching lineation initially formed during top-N shearing across the Dajiling fault and subsequently experienced drag (forced) folding during top-down-to-the-NE slip across the Rujiao fault. It is also feasible that the Niuku anticline was amplified during top-N thrusting across the GCT, possibly as a fault-bend fold above a footwall ramp (Figure 5). However, $^{40}\text{Ar}/^{39}\text{Ar}$ white mica ages from meta-Tethyan rocks in the anticline (38–27 Ma) [Laskowski *et al.*, 2016] predate slip across the GCT, suggesting that if folding related to the GCT occurred, it was not accompanied by substantial erosion.

The presence of structurally repeated, mesoscale (~ 1 m thick) to macroscale (~ 100 m thick) lenticular bodies (Figure 4a) of quartzite and paragneiss with distinct detrital zircon age spectra (Zq) within Cambrian-Ordovician meta-Tethyan rocks (see detrital zircon correlations in section 7.1) indicates substantial deformation within the Dajiling fault footwall. We interpret that Cambrian-Ordovician Tethyan Himalaya sequence rocks (COg) and quartzite and paragneiss lenses were interleaved by ductile shearing prior to or during Dajiling fault activity, as the lenticular rock bodies are foliation parallel (Figure 4a). Outcrop exposures of unit Zq were mapped in the field and extended laterally up to ~ 20 km using Landsat and Google Earth orthoimagery (Figure 3).

Within ~ 200 m of the Dajiling and Rujiao range-bounding faults, protomylonitic to mylonitic fabrics, cataclasite zones, breccia, and gouge overprint macroscopic foliation. Brittle structures replace ductile mylonitic fabrics from structurally lower to higher levels in the shear zones, indicating a progression from brittle-ductile to brittle deformation during progressive footwall unroofing. The kinematics and timing of the Rujiao and Lopukangri faults, which crosscut all other structures in the map area, indicate that they are related to Miocene-recent orogen-parallel ($\sim$ E-W) extension [Sanchez *et al.*, 2013; this study]. Fault scarps that likely represent synthetic hanging wall splays were mapped in glacial moraines that flank the range (Figure 3).

Figure 7. (a) Photomicrograph and (b) backscattered electron (BSE) image of microstructures in sample 61812AL5, which is representative of map unit COg. Dashed lines in the optical image highlight S1 foliation. S2 foliation, which is the macroscopic foliation throughout the map area, truncates this fabric. Phe = phengite; chl = chlorite; tur = tourmaline (dravite); and ap = apatite.

5.2. Microtextural Observations and Mineral Paragenesis

Electron microprobe analyses were paired with microscale to macroscale structural observations to interpret the relative timing of deformation and metamorphic events. Mineral species were identified using a PGT-5000 energy dispersive spectrometry (EDS) detector at the University of Arizona and quantified using wavelength-dispersive spectrometry. These data were combined with thermobarometry and geochronologic constraints presented in *Laskowski et al.* [2016], enabling interpretation of a generalized pressure-temperature-time-deformation (P-T-t-d) path.

EDS and petrographic analysis reveal that high-grade meta-Tethyan rocks are characterized by four typical lithologies: phengite-chlorite-albite-quartz-tourmaline schist, chlorite-phengite-calcite-quartz-albite-tourmaline±staurolite schist, phengite-chlorite-quartz-albite±ilmenite±staurolite metagreywacke, and quartzite with minor albite, phengite, staurolite, and biotite. Most samples contain rutile, apatite, zircon, and allanite as accessory phases. One metagreywacke sample contains garnet (7614AL3). Albite porphyroblasts are compositionally pure ($Ab > 99\%$), and garnets in sample 7614AL3 are spessartine and almandine rich in composition [*Laskowski et al.*, 2016].

Microtextural analysis reveals the presence of asymmetric inclusion trails composed primarily of phengite and tourmaline in albite and garnet alongside the later-formed macroscopic foliation composed primarily of phengite, chlorite, and staurolite (e.g., sample 61812AL5; Figure 7). We interpret that the primary foliation formed during prograde metamorphism; Si contents in phengite inclusions record pressures up to ~ 2.0 GPa [*Laskowski et al.*, 2016]. Matrix phengite records pressures ≥ 1.4 GPa, possibly indicating decompression related to tectonic exhumation along the retrograde path. Zr-in-rutile geothermometry indicates that the maximum temperature of metamorphism was $\leq 600^\circ\text{C}$, which was likely attained during retrogression at midcrustal depths (20–30 km) [*Laskowski et al.*, 2016].

6. Geochronology and Thermochronology

6.1. U-Pb Methods

Samples were disaggregated using traditional crushing methods. Minerals were separated using density and magnetic techniques. An aliquot of grains ($n = 1000\text{--}2000$) from each detrital zircon sample was mounted alongside fragments of natural zircon reference materials (i.e., Sri Lanka, R33, FC-1) in a 1 inch epoxy ring form. Prior to isotopic analysis, samples were sanded to a depth of $\sim 20\text{ }\mu\text{m}$, polished, and cleaned in a 1% HNO_3 and 1% HCl acid solution for 120 s.

U-Pb analyses were conducted using laser ablation inductively coupled plasma mass spectrometry (ICP-MS) [*Gehrels et al.*, 2006, 2008]. For detrital samples, 100–300 zircons were selected for analysis at random. For igneous samples, 30–50 zircons were analyzed per sample. Cathodoluminescence (CL) imagery was acquired

for igneous samples to target specific growth zones. Zircons were ablated using a Photon Machines Analyte G2 excimer laser with a beam size that varied from 30 to 10 μm according to the size of the target zone. The net effect of the ablation process produced pits on the zircon crystals that were $\sim 15 \mu\text{m}$ deep. The ablated material was transported in helium to the plasma source of the ICP-MS, which measured U, Th, and Pb isotopes. Two instruments acquired data: a Nu Plasma HR multicollector ICP-MS and a Thermo Scientific Element 2 HR single-collector ICP-MS. Measurements on the Nu were conducted in static mode using Faraday collectors with $3 \times 10^{11} \Omega$ resistors for ^{238}U , ^{232}Th , ^{208}Pb – ^{206}Pb , and discrete dynode ion counters for $^{204}(\text{Pb} + \text{Hg})$ and ^{202}Hg . When a 10 μm spot size was used, U and Th were measured using Faraday collectors and ^{208}Pb – ^{204}Pb were measured using ion counters [Gehrels *et al.*, 2008].

Analyses completed on the Element 2 were made in low resolution using E-scans to jump through the masses from 202 to 238. Dwell times were as follows: ^{202}Hg 5.2 ms, $^{204}(\text{Pb} + \text{Hg})$ 7.8 ms, ^{206}Pb 20.2 ms, ^{207}Pb 28.4 ms, ^{208}Pb 2.6 ms, ^{232}Th 2.6 ms, and ^{238}U 10.4 ms for an integration of four samples per peak. The total time for each analysis was 24 s composed of 73 runs (i.e., sweeps) with 6 s for baselines at the beginning, 14 s of ablation, and 6 s at the end for washout. Zircon was ablated at 7 Hz and 7.0 mJ in constant energy mode with laser energy density of 10.17 J/cm².

Individual analyses carry analytical uncertainties of 1–2% (2σ) for $^{206}\text{Pb}/^{238}\text{U}$ ages that result from uncertainty in determining $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{204}\text{Pb}$. Errors in measurement of $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ produce similar 1–2% (at the 2 sigma level) uncertainties for $>1.0 \text{ Ga}$ $^{206}\text{Pb}/^{207}\text{Pb}$ ages. However, analytical error in determining $^{206}\text{Pb}/^{207}\text{Pb}$ ages substantially increases for zircon grains with ages $<1.0 \text{ Ga}$. The cutoff for reporting $^{206}\text{Pb}/^{238}\text{U}$ versus $^{206}\text{Pb}/^{207}\text{Pb}$ ages averages $\sim 1.0 \text{ Ga}$ but is adjusted for each sample to avoid dividing clusters of $\sim 1.0 \text{ Ga}$ analyses.

Interelement fractionation of Pb/U ($\sim 5\%$) and Pb isotopes ($<0.2\%$) was corrected using standard sample bracketing with fragments of the Sri Lanka zircon reference material (Nu) or a suite of Sri Lanka, FC-1, and R33 zircon reference materials (Element 2). The Sri Lanka zircon crystal has a $^{206}\text{Pb}/^{238}\text{U}$ age of $563.5 \pm 3.2 \text{ Ma}$ (2σ), whereas R33 has a $^{206}\text{Pb}/^{238}\text{U}$ age of $419.26 \pm 0.39 \text{ Ma}$ (2σ) and FC-1 has a $^{207}\text{Pb}/^{206}\text{Pb}$ age of $1099.0 \pm 0.6 \text{ Ma}$ (2σ) [Paces and Miller, 1993; Black *et al.*, 2004; Gehrels *et al.*, 2008]. Concentrations of U and Th were also determined relative to known quantities in the Sri Lanka zircon, which are 518 ppm of U and 68 ppm of Th. ^{204}Hg interference with ^{204}Pb was corrected by measuring ^{202}Hg during laser ablation and subtracting ^{204}Hg according to the natural $^{202}\text{Hg}/^{204}\text{Hg}$ of 4.35. Hg-corrected ^{204}Pb and an assumed initial Pb composition [Stacey and Kramers, 1975] were used to correct for common Pb. Uncertainties of 1.5% for $^{206}\text{Pb}/^{204}\text{Pb}$ and 0.3% for $^{207}\text{Pb}/^{204}\text{Pb}$ were applied to the compositional values based on observed variation in Pb isotopic composition in modern crustal rocks.

Igneous U-Pb analytical data are reported in supporting information Table S2, and igneous zircon U-Pb data are reported in supporting information Table S3. Graphical U-Pb age determinations are shown in Figures 8 and 9. U-Pb analyses with $>20\%$ discordance (determined by comparison of $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ ages) or $>5\%$ reverse discordance were not considered. Interpreted detrital zircon U-Pb ages based on the above corrections are plotted as probability density functions in Figure 9 using an in-house Excel program (available from <http://www.laserchron.org>) that normalizes single curves such that each contains the same area. Age probability peaks and populations (ranges of ages) were determined using the in-house AgePick program (available from <http://www.alc.org>). This program was also used to guide interpretation of crystallization ages for igneous samples. The rationale for each maximum depositional age (detrital) interpretation is listed in supporting information Table S1.

6.2. U-Pb Igneous Zircon Results

Eleven granitic rocks were collected from bedrock exposures in the Lopu Range region for zircon U-Pb geochronology. Most samples were collected from plutons and dikes that intrude the horst block located between the Lopukangri and Rujiao faults. Two samples were collected from the Gangdese batholith to the west and east of the Lopukangri and Rujiao faults, respectively (Figure 3). Igneous U-Pb samples were divided into three groups based on their age distributions and chemistry: (1) Gangdese arc granodiorites that contain no xenocrystic zircon cores (Figure 8a), (2) Gangdese arc granitoids that contain xenocrystic zircon cores (Figure 8b), and (3) Miocene leucogranites that contain abundant xenocrystic zircon cores (Figure 8c).

Figure 8. Igneous U-Pb data from (a) Gangdese batholith rocks, (b) Gangdese batholith rocks with xenocrystic zircon, and (c) leucogranites. Figure 8a displays weighted mean age determinations only, whereas Figures 8b and 8c display weighted mean age determinations (dark blue ages), xenocrystic zircon ages (light blue), and probability distribution functions with histograms of xenocrystic zircon ages (right).

Group 3: Leucogranite U-Pb Results

Group one samples (Figure 8a) all yielded abundant zircon; CL imagery revealed homogeneous or oscillatory-zoned structures with no clear core and rim relationships. Sample 62011PK6—a potassium feldspar-bearing phyrlic granite from the Gangdese batholith northeast of Lopu Kangri—produced a weighted mean age of 48.5 ± 0.5 Ma (mean square weighted deviate (MSWD) = 0.6). Sample 62012AL1—a potassium feldspar-bearing granite in the Rujiao fault footwall that intrudes sedimentary-matrix mélangé—produced an age of 46.7 ± 0.7 Ma (MSWD = 1.11). Sample 62212AL2—a potassium feldspar-bearing phyrlic granitic dike also located in the Rujiao fault footwall—produced a weighted mean age of 38.0 ± 0.3 Ma (MSWD = 0.87) (Figure 3).

Figure 9. Detrital zircon data plotted as normalized probability density functions. Ages <250 Ma are plotted in the left side panel (100% scale), and ages between 250 and 3000 Ma are plotted on the right side panel (130% scale). The bottom panel displays age spectra from potential Indian and Asian source areas [Gehrels *et al.*, 2011; Orme *et al.*, 2015]. The top panel displays new detrital zircon data presented in this study classified by Indian or Asian provenance. Samples derived from Indian source regions have an age probability peak between ~450 and 600 Ma (shaded) and no ages younger than 100 Ma, which is the age of the youngest zircons in the Tethyan Himalaya Sequence. Samples derived from Asia have ages <100 Ma (shaded), which can be derived from the igneous rocks in the Lhasa terrane or recycled from the Xigaze fore-arc basin (Saga area fore arc). Maximum depositional ages (MDA) interpreted as reliable are reported next to the appropriate age probability peak. The rationale for each MDA interpretation is provided in supporting information Table S1.

Group two samples are similar in age to group one samples; however, xenocrystic zircons with low-U/Th cores and high-U/Th rims (up to ~ 20) are common (Figure 8b). High-U/Th ratios are interpreted as evidence for crystallization in the presence of fluids related to metamorphism as monazite preferentially incorporates Th [Rubatto *et al.*, 2001; Williams, 2001; Gehrels *et al.*, 2008]. Sample 62512AL1—a chloritized and brecciated granitoid along the northeastern range front that intrudes sedimentary-matrix *mélange* (Figure 3)—produced an age of 37.1 ± 0.6 Ma (MSWD=4.5) based on the weighted mean of the youngest population ($n=5$). Targeted analyses of xenocrystic zircon cores reveal a dominance of 50–60 Ma and >400 Ma ages ($n=38$). Sample 71314AL6—a phaneritic granodiorite collected in the Gangdese Mountains to the west of Lopu Kangri (Figure 3)—produced an age of 40.3 ± 0.4 Ma (MSWD=4.6) based on the weighted mean of the youngest population ($n=30$). Four xenocrystic zircon core analyses produced ages between 57 and 43 Ma. The higher-than-optimal MSWD values in both samples might reflect longer-duration zircon crystallization than analytical precision or mixing between crystallization age rims and xenocrystic cores during ablation.

Group three samples (7112AL2, 7112AL4, 62312AL2, 62712AL1, 62712AL2, and 71414AL1) are leucogranites that contain complexly zoned zircons consisting of low- to high-U/Th cores and volumetrically minor (typically $<20 \mu\text{m}$) high-U/Th rims (Figure 8c). Crystallization ages are all between 15.6 ± 0.4 and 16.6 ± 0.3 Ma, while xenocrystic zircon cores range in age from Miocene to Proterozoic (Figure 8c). Eocene–Miocene zircons display higher-U/Th ratios (up to ~ 200) than both group one and group two samples (Figure 8c). Leucogranites are both undeformed and variably sheared and are confined to the Lopu Range horst block, between and often in close proximity to the Lopukangri and Rujiao faults. They intrude sedimentary-matrix *mélange*, older Gangdese arc granitoids, and meta-Tethyan rocks. Sample 7112AL2 (16.2 ± 0.3 Ma) cuts a top-down-to-the-north, normal-sense footwall splay of the Lopukangri fault in a glacially carved canyon along the western Lopu Range front (Figure 3), providing a minimum age for the onset of E–W extension. A $\sim 70 \text{ km}^2$ leucogranite pluton intrudes the southwest Lopu Range and is exposed in the footwall of the Lopukangri fault (Figure 3). Two samples from this pluton (71414AL1 and 62712AL2) produced crystallization ages that are indistinguishable from the leucogranite dikes.

6.3. U–Pb Detrital Zircon Results

Fourteen detrital zircon samples were collected from the Lopu Range map area (Figure 3) to determine maximum depositional ages (MDAs), test lithologic correlations, and make provenance interpretations. Six samples were collected from units that we correlate to the southern margin of the Lhasa terrane on the geologic map. These include one sample from the Kailas Formation (71314AL2), two samples from metaconglomerate blocks in the sedimentary-matrix *mélange* (62512AL4 and 62912AL2), and three samples from Xigaze fore-arc strata (71314AL4, 71314AL3, and 61911PK1). The remaining samples (62112AL1, 62112AL2, 7312AL2, and 7112AL3) were collected from Indian-affinity metasedimentary rocks in the southern Lopu Range (Figure 3).

Detrital zircon samples were collected from mesoscale to macroscale lenses of quartzite and paragneiss that compose unit Zq and schist, paragneiss, and quartzite that compose unit COg (Figure 3). Sample 7112AL3 was collected from an outcrop-scale lens of quartz-rich paragneiss intruded by leucogranite (sample 7112AL2) in schist, while samples 71814AL2 and 7614AL1 were collected from laterally continuous quartzite bodies in paragneiss and schist that were revealed to neck along strike based on satellite imagery and field mapping (Figure 3). These three samples, all from unit Zq (Figure 3), are characterized by prominent ~ 2.5 Ga, 2.0–1.5 Ga, and 1.0 Ga to 750 Ma age probability peaks (Figure 9). The youngest zircons in these samples are Neoproterozoic, defining maximum depositional ages >750 Ma (supporting information Table S1). The samples from surrounding meta-Tethyan paragneiss, schist, and quartzite (71914AL3, 7312AL2, 62112AL2, and 62112AL1; unit COg) display less prominent Archean and Paleoproterozoic age probability peaks that accompany more prominent Mesoproterozoic to Neoproterozoic age probability peaks. The youngest zircons in these samples are Cambrian–Ordovician, defining maximum depositional ages between 540 and 450 Ma (supporting information Table S1).

Three samples were collected from clastic sedimentary rocks that were correlated to Xigaze fore-arc strata (KEx) during field mapping, two from northwest of the Lopu Range along the Gangdese Shan (71314AL3 and 71314AL4) and the third from north of Lopu Kangri (61911PK1) (Figure 3). The detrital zircon age spectra obtained from these samples are similar to a composite of 18 Lopu Range region Xigaze fore-arc detrital zircon samples presented in Orme *et al.* [2015], supporting our field correlations (Figure 10). Sample 71314AL3

was collected from the sandy matrix of a ~5 m thick, tabular conglomerate bed composed of dominantly volcaniclastic sandstone and red shale clasts. We interpret a depositional contact between the conglomerate and underlying serpentinite mélange based on the absence of evidence for faulting between the units and contact-parallel bedding (114, 65°SW) in the conglomerate and overlying strata (Figures 4b and 11a). This relationship is preserved in a tectonic sliver within the north vergent GCT fault zone, bounded by gouge and locally pseudotachylite-bearing cataclasite zones above the conglomerate and structurally below the mélange (Figures 4b and 11a). Detrital zircons in 71314AL3 range in age from Archean to Cenozoic with dominant age probability peaks at ~700–500 Ma and ~97 Ma and a Middle Cretaceous MDA of 97.2 ± 1.2 Ma (supporting information Table S1). Sample 71314AL4 was collected outside the tectonic sliver from a ~1.5 m thick sandstone bed ~10 m above the conglomerate sample, across a ~1 m thick shale layer that is disrupted by a thin (~0.25 m) pseudotachylite-bearing cataclasite zone. This sample displays a similar detrital zircon age spectrum to that of sample 71314AL3, but the youngest ages ($n = 39$) define a Late Cretaceous MDA of 79.7 ± 1.5 Ma (supporting information Table S1). Sample 61911PK1 was collected from lithic sandstone exposed at the terminus of a glacial lateral moraine along the northeast Lopu Range, in the proximal hanging wall of the Rujiao fault (Figure 3). This sample displayed a similar age spectra to the other Xigaze fore-arc samples and produced a MDA of 83.9 ± 1.1 Ma (supporting information Table S1). Previous studies of the Xigaze fore-arc basin indicate that MDAs are a close approximation of true depositional age in most cases, as the Gangdese magmatic arc provides a proximal source of young zircons [e.g., Orme *et al.*, 2015; Hu *et al.*, 2016].

Samples 62912AL2 and 62512AL4 were collected from penetratively strained, amphibolite facies metaconglomerate blocks in sedimentary-matrix mélange (mlg) on the west and east sides of the Lopu Range, south of Lopu Kangri (Figure 3). Sample 62512AL4 is an L-tectonite with a pronounced E-W lineation defined by chert- and shale-protolith clasts with aspect ratios up to 8:1. Sample 62912AL2 appeared similar in composition yet was not an L-tectonite and was overprinted by cataclasis related to slip across the Lopukangri fault. Sample 62912AL2 produced a similar age spectrum to those of the Xigaze fore-arc samples, with a dominant age probability peak centered at ~520 Ma and a MDA of 68.1 ± 5.6 Ma ($n = 6$; supporting information Table S1). Sample 62512AL4 yielded few zircons ($n = 23$); the two youngest overlapping grains yield a poorly constrained MDA of 58.6 ± 8.8 Ma (supporting information Table S1). Detrital zircons younger than ~250 Ma are distributed similarly in both samples (Figure 9).

Sample 71314AL2 from a sand interval within the Kailas Formation to the west of Lopu Kangri (Figure 3) yielded Cretaceous–Paleocene (150–50 Ma) and Proterozoic (2.5–0.5 Ga) detrital zircon ages (Figure 9) with an MDA of ~53 Ma (supporting information Table S1). Previous studies of the Kailas Formation in the Lopu Range region [Sanchez *et al.*, 2013] and along strike in the Yarlung suture zone [e.g., DeCelles *et al.*, 2011] indicate an Oligocene–Miocene depositional age. The observation that Gangdese arc magmatism ceased at ~37 Ma in southern Tibet [Kapp *et al.*, 2007] is a possible explanation for a lack of depositional age detrital zircons in this sample. Moreover, zircons from Oligocene–Miocene leucogranites exposed in the footwall of Lhasa terrane rifts (e.g., North Lunggar) [Kapp *et al.*, 2008; Sundell *et al.*, 2013] contain abundant xenocrystic zircon cores and volumetrically minor, easily erodible crystallization age rims that might have been destroyed during erosion and transport.

Sample 62011PK4 was collected from a ~2 m block of chevron-folded, hornblende-plagioclase paragneiss intercalated with serpentinite and gabbro blocks in a tectonic sliver along the GCT east of Lopu Kangri (Figures 3 and 11b). This zircon-poor sample, which is not shown in Figure 9 due to the small number of analyses ($n = 12$), yielded ages between 234 and 165 Ma all with U/Th ratios ≤ 2.3 . The broad distribution of ages and a lack of evidence for metamorphic zircon growth suggest a sedimentary protolith. The youngest age probability peak ($n = 5$) defines a maximum depositional age of 169 ± 4 Ma with a MSWD of 1.9 (supporting information Table S1).

6.4. Zircon (U-Th)/He Methods

Zircon (U-Th)/He analyses were conducted at the Arizona Radiogenic Helium Dating Laboratory (<http://www.geo.arizona.edu/~reiners/arhdi/arhdi.htm>) following the procedures outlined in Reiners *et al.* [2004] and Reiners [2005]. Zircons with euhedral morphologies, minimal inclusions, minimal fractures, maximum clarity, and with radii $>60 \mu\text{m}$ were handpicked for analysis. The dimensions of individual grains were measured from photomicrographs following the procedures outlined in Hourigan *et al.* [2005] to calculate correction

Figure 10. Visual comparisons of samples from this study with Xigaze fore-arc detrital zircon data from the Lopu Range region [Orme *et al.*, 2015], the Tethyan Himalaya sequence composite reference curve [Gehrels *et al.*, 2011], the Greater Himalaya sequence composite reference curve [Gehrels *et al.*, 2011], and a Lower Cambrian Tethyan Himalaya sequence sample that displays an atypical age spectrum (MS-2) [Myrow *et al.*, 2010].

factors. Three to five grains from each sample were packed and sealed in 1 mm Nb foil tubes and loaded into a vacuum laser cell. During analysis, individual packets were heated for 15 min using a focused beam from a 1–2 W laser to extract ^4He . Gas released from samples was spiked with 0.1–0.2 pmol ^3He then condensed onto activated charcoal within a cryogenic trap at 16°K. Helium was then heated to 37°K and released into a small volume ($\sim 50\text{ cm}^3$) container with an activated Zr-Ti alloy getter. Zircons were reheated at least one time for 15–20 min until reextracted ^4He yields were less than 2% of the compounded total. Fish Canyon Tuff zircon standards with a zircon (U-Th)/He age of $28.48 \pm 0.06\text{ Ma}$ at 2σ [Schmitz and Bowring, 2001] were analyzed between every 5–7 unknowns.

Figure 11. Detailed geologic maps of the Great Counter Thrust system to the (a) west and (b) east of Lopu Kangri peak, displaying geochronology sample locations and results. Symbols and map locations are indicated in Figure 3.

$^4\text{He}/^3\text{He}$ ratios were measured using a quadrupole mass spectrometer equipped with a Channeltron electron multiplier, and the intercept was determined by regressing corrected $^4\text{He}/^3\text{He}$ ratios through 10 measurement cycles ~ 15 s in duration, yielding an uncertainty of 0.05–0.5% over $^4\text{He}/^3\text{He}$ ranges of $\sim 10^3$. Values were compared to the mean corrected ratio to check for significant fractionation during analysis. He contents were calculated by subtracting the average mass 1-corrected $^4\text{He}/^3\text{He}$ measured on multiple line blanks from the mass 1-corrected $^4\text{He}/^3\text{He}$ measured on the unknowns. The result was then divided by the mass 1-corrected $^4\text{He}/^3\text{He}$ measured on a standard spike of online reference ^4He measured in the same manner. The resultant ratio was then multiplied by the moles of ^4He injected in the spike.

Following He extraction and measurement, Nb packets were retrieved, transferred to Teflon vials, and spiked with 0.5–1.0 ng of ^{233}U and ^{229}Th . Zircons were then dissolved in their Nb packets using high-pressure digestion vessels. Natural-to-spike isotopic ratios of U and Th were measured using a high-resolution single-collector Element2 ICP-MS. All sample introduction and preparation/analytical equipment used were made of all-PFA Teflon. Zircon analysis blanks are 2.6 ± 0.5 pg U and 5.5 ± 0.1 pg Th. Measured U-Th ratios are typically reproducible within 0.5%. Propagation of analytical uncertainties for typical zircon samples leads to analytical uncertainty of (U-Th)/He ages of 1–3% at 1σ . Repeat analyses of (U-Th)/He ages are significantly less reproducible than analysis of multiple aliquots from one sample, which approaches analytical precision. Single-grain zircon (U-Th)/He analytical data are provided in supporting information Table S4 and illustrated in Figure 12. Reported ages are mean ages determined by averaging 2–5 grains per sample to allow for exclusion of outliers.

6.5. Zircon (U-Th)/He Results

Zircon (U-Th)/He ages were determined for seven samples of Neogene granite (62712AL2 and 62312AL2), Paleogene granite (62012AL1, 62512AL1, 7112AL4, and 62212AL2), and meta-Tethyan quartzite (7312AL2) collected from the horst block of the Lopu Range (Figures 3 and 12). Two additional ages were determined for a sample of Gangdese arc granodiorite (62011PK6) in the northeast quadrant of the geologic map and the paragneiss intercalated with ophiolitic mélange in a tectonic sliver (62011PK4; Figures 2 and 5). The Gangdese arc sample (62011PK6) yielded an age of 19.6 ± 0.4 Ma, while the paragneiss (62011PK4) yielded an age of 107.3 ± 2.2 Ma.

Within the horst block, zircon (U-Th)/He ages are 12–6 Ma (Figure 12a). The oldest age (11.8 ± 0.2 Ma) is from the southernmost sample. The youngest age (6.0 ± 0.1 Ma) is from the sample that was collected ~ 200 m away from the northeast range-bounding fault, east of Lopu Kangri peak. Zircon (U-Th)/He ages in the horst block show a rough inverse correlation with sample elevation (Figure 12b), no correlation with grain radius, and no correlation with eU (supporting information Table S4). Footwall zircon (U-Th)/He ages show a strong correlation with average horizontal distance measured perpendicular to range-bounding faults (Figure 12c).

7. Discussion

7.1. Age and Provenance of Indian-Affinity Rocks

The high metamorphic grade and penetrative ductile deformation of Indian-affinity schist, gneiss, and quartzite complicates lithostratigraphic correlation and biostratigraphic dating. Therefore, detrital zircon geochronology is the most effective technique for constraining their maximum depositional age and provenance. Two different characteristic age spectra characterize the metasedimentary rocks: three samples contain only Proterozoic-Archean ages, whereas the remaining four samples contain Paleozoic ages. The full range of ages in these samples can be explained by derivation from Lhasa terrane (Eurasia) and Indian (metasedimentary) sedimentary and plutonic sources, which are the most proximal provenance candidates. The youngest ages in all samples are too young to have been sourced solely from the Early to Middle Proterozoic lower Lesser Himalaya strata [e.g., *DeCelles et al.*, 2000], which are characterized by detrital zircon U-Pb ages older > 1.6 Ga [*Gehrels et al.*, 2011].

Greater Himalaya sequence rocks are Neoproterozoic in age, contain no detrital zircons < 550 Ma, and are intruded by 550–400 Ma igneous rocks [*DeCelles et al.*, 2000; *Gehrels et al.*, 2011]. Tethyan Himalaya sequence rocks typically contain detrital zircons < 550 Ma and were likely derived from Greater Himalayan rocks and accompanying plutons [*DeCelles et al.*, 2000; *DeCelles et al.*, 2016b]. Visual comparison of detrital zircon age spectra from unit COg (samples 71914AL3, 7312AL2, 62112AL2, and 62112AL1) with representative

Figure 12. (a) Zircon (U-Th)/He ages with 1 sigma errors from the Lopu Range horst block plotted on a simplified geologic map. The location of sample 62212AL2 is provided in Figure 3. Each sample's interpreted age (pink) and individual analyses (blue) are plotted with 1 σ errors as a function of (b) elevation and (c) average distance measured orthogonal to the Lopukangri and Rujiao faults.

composite spectra from candidate source terranes reveals a good match with the Tethyan Himalaya sequence (Figures 9 and 10). The youngest zircons in COg samples produce maximum depositional ages between 535 and 437 Ma (supporting information Table S1). These data support our interpretation that the protoliths of unit COg were Cambrian-Ordovician strata of the Tethyan Himalaya sequence. Visual comparison of detrital zircon age spectra from unit Zq (samples 71814AL2, 7614AL1, and 7112AL3; Figure 3) with candidate source terranes reveals a mismatch with the Tethyan Himalaya sequence but a good match with the Greater Himalaya sequence (Figures 9 and 10). However, Zq samples are also indistinguishable from a lower Cambrian Tethyan Himalaya sequence sample (MS-2; Figure 10), collected ~500 km west of the Lopu Range [Myrow *et al.*, 2010]. The absence of detrital zircons <700 Ma in sample MS-2, despite the presence of early Cambrian trilobites in the unit, was interpreted to reflect deposition prior to Middle-Late Cambrian unroofing of Gondwanan orogenic belts [Myrow *et al.*, 2010]. Based on the available data, two correlations are permissible: (1) the Zq samples correlate with Early Cambrian Tethyan Himalaya sequence rocks that display atypical detrital zircon age spectra or (2) the Zq samples correlate to the Neoproterozoic Greater Himalaya sequence. Lower Cambrian Tethyan Himalaya sequence strata were deposited unconformably atop the Greater Himalaya sequence [e.g., Gehrels *et al.*, 2011; DeCelles *et al.*, 2016b]; therefore, the stratigraphic separation required to tectonically interleave Zq samples with unit COg (Figure 3) is not significantly different for either interpretation. Further investigation of the detrital zircon signatures of lower Cambrian Tethyan Himalaya sequence strata is required to definitively correlate Zq samples (Figures 9 and 10).

Continental (U)HP metamorphic complexes along the Indus-Yarlung suture have similar protolith ages. The Lopu Range complex consists of Lower Cambrian to Late Ordovician metapelite, metagreywacke, calcparagneiss, and quartzite at its core, mantled by Permian phyllite. Both Kaghan Valley and Tso Morari are cored by Neoproterozoic orthogneiss with eclogitic metamafic enclaves overlain by retrogressed eclogite-facies metagreywacke and metapelites of Neoproterozoic or Early Paleozoic age [Spencer *et al.*, 1995; Draganits *et al.*, 1998; Treloar *et al.*, 2003]. Lower metamorphic-grade Permian metasedimentary rocks (e.g., the Tetragonal nappe at Tso Morari) structurally overlie lower Paleozoic metasedimentary rocks at all three localities [Spencer *et al.*, 1995; Epard and Steck, 2008; Guillot *et al.*, 2008; Laskowski *et al.*, 2016]. The major difference between the Lopu Range and the other (U)HP metamorphic complexes along the Indus-Yarlung suture is that Neoproterozoic orthogneiss, which hosts the eclogite lenses at Kaghan Valley and Tso

Morari, is not exposed. The lack of a mafic protolith at the currently exposed structural level may explain the lack of eclogite-facies rocks at the core of the Lopu Range complex [Laskowski *et al.*, 2016].

7.2. Development of the Lhasa Terrane Convergent Margin

Gangdese arc, Xigaze fore-arc, ophiolitic mélange, and sedimentary-matrix mélange rocks are key to understanding the architecture of the southern margin of Asia prior to intercontinental collision. In the Lopu Range region, these units provide a record of Jurassic-Paleocene convergent margin development, which took place during northward subduction of Neo-Tethyan oceanic lithosphere. The well-exposed Cretaceous-Paleogene geology is supplemented by rare exposures of pre-Cretaceous rocks, providing limited constraints on early margin development. In the Lopu Range region, the only pre-Cretaceous Lhasa terrane rock is a hornblende-plagioclase-epidote paragneiss block exposed in a tectonic sliver with serpentinite- and gabbro-block ophiolitic mélange along the Great Counter Thrust northeast of Lopu Kangri (sample 62011PK6; Figure 11). This rock contains Middle Triassic to Middle Jurassic detrital zircons and has a MDA of 169 ± 4 Ma (supporting information Table S1). Zircon (U-Th)/He thermochronology indicates that the sample cooled below $\sim 180^\circ\text{C}$ [Reiners *et al.*, 2004] at 107 ± 2 Ma. We interpret that the protolith was deposited south of the Lhasa terrane margin, possibly in a Triassic-Jurassic back arc or interarc basin [e.g., Guilmette *et al.*, 2012]. Later, the sample was metamorphosed at amphibolite facies conditions—possibly in the metamorphic sole—as ophiolitic rocks were obducted southward over sedimentary-matrix mélange. Therefore, subduction initiation must have occurred between 169 and 107 Ma, consistent with 132–127 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the Saga ophiolite metamorphic sole immediately east of the Lopu Range map area [Guilmette *et al.*, 2012].

Xigaze fore-arc basin strata, derived primarily from Gangdese magmatic arc rocks, provide a geologic record of the configuration of the southern margin of Asia during Cretaceous-Paleocene time [e.g., Einsele *et al.*, 1994]. However, the GCT largely obscures the primary relationship between Xigaze fore-arc strata and ophiolitic mélange along the Yarlung suture. The resulting ambiguity permits a broad range of tectonic models in which the Jurassic-Cretaceous ophiolitic rocks were either obducted onto India far outboard of Eurasia, prior to India-Asia collision, or proximal to the Lhasa terrane during the onset of collision. The freedom afforded by this uncertainty is in part responsible for the broad range of proposed collision ages [e.g., Ding *et al.*, 2005; Aitchison *et al.*, 2007].

Depositional contacts between ophiolitic mélange, volcanoclastic conglomerate, and overlying Xigaze fore-arc strata are exposed in a tectonic sliver along the GCT northwest of Lopu Kangri (Figure 11a), along strike of the hornblende-plagioclase-epidote paragneiss block (Figure 11b). A depositional contact between Xigaze fore-arc basin strata and ophiolitic mélange was also observed ~ 300 km to the east near the town of Lazi [Orme and Laskowski, 2016] (Figure 1). Detrital zircons from the sandstone matrix of the conglomerate yield a MDA of 97 ± 1 Ma (sample 71314AL3). We interpret that the conglomerate and overlying sandstone and shale layers within the tectonic sliver represent the basal Xigaze fore arc and were deposited atop ophiolitic mélange. Therefore, the Early Cretaceous ophiolitic rocks [Hébert *et al.*, 2012] likely formed in a fore-arc setting above the Neo-Tethyan-Lhasa terrane subduction zone, consistent with paleomagnetic data [Huang *et al.*, 2015]. South Tibetan ophiolitic rocks and underlying ophiolitic mélange are constrained by radiolarian biostratigraphy, geochronology, and $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology to have formed between 132 and 117 Ma [Maffione *et al.*, 2015]. If these ages apply to the ophiolitic mélange in the Lopu Range region, then the time gap between ophiolite formation and the deposition of basal Xigaze fore-arc strata is ≥ 20 Myr. Fore-arc extension to tectonically exhume ophiolitic mélange [e.g., Maffione *et al.*, 2015] might have produced spatial variations in the ages of basal fore-arc sedimentation (Figure 13a), which is >20 Myr older (~ 125 – 120 Ma) near the town of Xigaze (~ 400 km to the east) [Wang *et al.*, 2012] than it is in the Lopu Range. Diachronous fore-arc extension beginning by ~ 110 Ma might also explain the 107 ± 2 Ma cooling age obtained from the paragneiss exposed along strike and the 97 ± 1 Ma MDA (Figure 13a) obtained from the basal Xigaze fore arc west of Lopu Kangri. These data suggest that the southern Lhasa terrane became a coherent, Cordilleran-style arc-fore-arc-trench system by ~ 97 Ma. There is no geological evidence in the Lopu Range region that supports the existence of two or more subduction zones south of the Xigaze fore arc during Late Cretaceous to Paleocene time.

Fore-arc basin deposition continued during Late Cretaceous to early Eocene time, transitioning from marine to fluvial by ~ 54 Ma [Orme *et al.*, 2015] (Figure 13a). Two additional fore-arc detrital zircon samples (61911PK1 and 71314AL4) have MDAs of 84 ± 1 Ma and 78 ± 2 Ma, respectively. Sample 61911PK1 from the hanging

Figure 13. (a) summary of tectonic events discussed in the text, including sedimentation, magmatism, deformation (extension and contraction), and metamorphism events with geochronologic and thermochronologic constraints (diamonds = U-Pb detrital zircon, boxes = zircon-He, and triangle = garnet Lu-Hf). Note nonlinear time scale. (b) P-T path of high-grade Indian metasedimentary rocks (COg and Zq) constrained by geochronology, thermochronology, and structural interpretations. The age of peak metamorphism is not well constrained but likely occurred soon after the garnet Lu-Hf age, interpreted to record prograde metamorphism [Laskowski *et al.*, 2016].

wall of the Rujiao fault along the northeast Lopu Range front is dominated by Cretaceous detrital zircons ($n = 74$ of 90), with similar ages to those of igneous rocks within the Gangdese magmatic arc (Figure 9). In sample 71314AL4, roughly half of the 316 zircons are older than 250 Ma. Non-Gangdese zircons in both samples fall within two age ranges between 500–650 Ma and 1000–1250 Ma, consistent with recycling of Lhasa terrane sedimentary sources (Figure 9).

Two detrital zircon samples from the amphibolite-grade metaconglomerate blocks within the sedimentary-matrix mélangé (62912AL2 and 62512AL4) yielded maximum depositional ages of 68 ± 6 and 59 ± 9 Ma, respectively. These samples contain detrital zircon age spectra that include the same populations as those of the Upper Cretaceous Xigaze fore-arc basin samples. Previous studies of the Xigaze fore-arc basin identified conglomeratic intervals within the Quxia and Jialazi formations, which were deposited between 66 and 54 Ma, possibly atop an intrabasin unconformity [Ding *et al.*, 2005; Orme *et al.*, 2015; Hu *et al.*, 2016]. Therefore, we interpret that these conglomerates either (1) represent trench fill that spilled over the outer fore-arc high of an overfilled Xigaze fore-arc basin between ~68 and 59 Ma or (2) were deposited within the fore-arc basin as part of the Quxia and Jialazi formations and were later tectonically incorporated into the sedimentary-matrix mélangé. The former scenario is consistent with the development of an unconformity within the basin

during latest Cretaceous time [Ding *et al.*, 2005]. The latter scenario implies that subduction erosion affected the Xigaze fore-arc basin (Figure 14b).

7.3. Onset of India-Asia Collision

By ~59 Ma, sediments derived from the Lhasa terrane were deposited atop Tethyan Himalaya sequence strata, signaling the imminent onset of India-Asia collision [DeCelles *et al.*, 2014; Hu *et al.*, 2016; Orme *et al.*, 2015]. High-pressure metamorphism of Tethyan rocks (Figure 13b) was ongoing by 40 ± 1 Ma at Lopu Kangri based on metamorphic petrology data and a garnet Lu-Hf age from a meta-Tethyan greywacke (unit COg), 6–7 My later than that of Tso Morari and Kaghan Valley (~47 Ma) in the northwest Himalaya (Figure 1) [Donaldson *et al.*, 2013; Laskowski *et al.*, 2016]. The discrepancy between the timing of sedimentary overlap and prograde metamorphism of meta-Tethyan rocks, constrained by the age of prograde metamorphism at Lopu Kangri, Tso Morari, and Kaghan Valley, reveals a 12–19 Myr lag that is not accounted for in most tectonic models. One explanation is that meta-Tethyan rocks in the Lopu Range were not located along the leading edge of the Indian continental plate. Alternatively, strain might have been accommodated by crustal thickening within the relatively weak, extended Greater Indian margin during the first ~15 Myr of India-Asia collision. Subsequent underthrusting of strong Indian crust (e.g., the Greater Himalaya sequence) could have caused a switch from “soft” to “hard” collision, driving continental subduction, HP metamorphism, and exhumation (Figures 13b and 14c). This scenario is consistent with the presence of lenses of quartzite and paragneiss with possible Greater Himalaya sequence affinity in meta-Tethyan rocks (Figure 13a), implying interaction prior to or during translation across the Dajiling fault (Figure 14d).

Penetrative fabrics and faults in the Lopu Range record deformation of Tethyan rocks as they were subducted, metamorphosed, and exhumed. Early formed fabrics—preserved as crenulation cleavage—were possibly generated during subduction and prograde metamorphism. Crosscutting fabrics, including the macroscopic foliation throughout most of the range and a pervasive, generally N-S oriented ductile lineation (Figure 6), formed during exhumation. These fabrics share a similar orientation and shear sense with the top-to-the-north Dajiling fault, which is interpreted as a passive roof structure that accommodated exhumation of HP Tethyan rocks in tandem with a structurally deeper reverse fault that is not exposed within the map area (Figure 2). This kinematic model (Figure 14) is similar in style to the predictions of the subduction channel return flow model of Beaumont *et al.* [2009], developed to explain the PTt path and structural architecture of the Tso Morari metamorphic complex and its analogs.

Initial subduction of the Tethyan Himalaya margin was likely steep, aided by a still attached Neo-Tethyan oceanic slab (Figures 14b and 14c). This is supported by the close proximity of Eocene Gangdese arc rocks to suture zone ophiolite and mélangé in the Lopu Range region and throughout southern Tibet (Figures 1 and 3). Subsequent breakoff of the leading slab (Figure 14c) might have triggered or temporally coincided with exhumation of Indian-affinity HP metasedimentary rocks, which was likely driven by positive buoyancy relative to the surrounding mantle or lower crust [e.g., Warren *et al.*, 2008]. A detached slab is present in the lower mantle below the restored latitude of the suture [Van der Voo *et al.*, 1999], possibly recording Neo-Tethyan slab breakoff (Figure 14c). The youngest Gangdese arc rocks are ~38 Ma. We suggest that following Neo-Tethyan slab breakoff, shallow northward underthrusting of India displaced the upper plate mantle wedge northward and shutoff arc magmatism (Figure 14d). The transition to shallow underthrusting is consistent with lithospheric-scale tectonic models based on both analog experiments [Chemenda *et al.*, 2000] and geological observations [DeCelles *et al.*, 2011]. It is likely that underthrusting of Greater Himalayan rocks increased the net buoyancy of Indian continental lithosphere as it was subducted beneath the southern Lhasa terrane. If this were the case, then the shutoff of arc magmatism at ~38 Ma coincides with initial underthrusting of Greater Himalaya sequence rocks beneath the southern Lhasa terrane, ~21 Myr after collision onset constrained by sedimentary overlap across the Indian and Asian continental margins [DeCelles *et al.*, 2014; Hu *et al.*, 2016] (Figure 14d).

The appearance of xenocrystic zircon in Gangdese arc samples records changes in magmatic arc behavior following the onset of India-Asia collision. Gangdese arc samples older than ~40 Ma (62512AL1 and 62012AL1; Figure 8a) intrude sedimentary-matrix mélangé of the Lhasa terrane subduction-accretion complex, possibly recording steep subduction and southward trench retreat following slab rollback and/or mélangé underplating during early to middle Eocene time. Gangdese arc samples that crystallized between 40 and 37 Ma (62512AL1 and 71314AL6; Figure 8b) contain 60–50 Ma xenocrystic zircon cores, accompanied

Figure 14. Kinematic model of Tibetan-Himalayan orogenesis between 59 and 16 Ma displaying episodes of faulting, underthrusting, and rollback of Indian lithosphere, sedimentation, and magmatic arc activity as indicated by the black triangles. Unit colors are keyed to Figure 3. The Kailas fault is possibly equivalent to the Ayi Shan detachment [Zhang *et al.*, 2011; DeCelles *et al.*, 2011].

by 400–2500 Ma cores in sample 62512AL1 (Figure 8b). Assimilation of previously formed zircon with ages representative of older Gangdese arc rocks and sedimentary rocks of the Lhasa terrane (Figure 9) might have resulted from subduction of trench fill sediments derived from the Gangdese magmatic arc and Lhasa terrane, subduction erosion of portions of the Xigaze fore-arc, and/or magmatic reworking of the Gangdese arc and Lhasa terrane lower crust. The first appearance of xenocrystic zircon cores in Gangdese arc rocks at ~40 Ma corresponds temporally with the transition to low-angle Indian underthrusting, immediately prior to ~38 Ma shutoff of arc magmatism in the southern Lhasa terrane [Kapp *et al.*, 2007] (Figures 13a and 14d). It is plausible that shallow underthrusting would favor subduction erosion of the southern Lhasa terrane and/or fore-arc uplift and resultant sedimentary bypass of the Xigaze fore-arc basin. The plausibility of magmatic reworking related to shallow underthrusting is unclear, though metamorphic and migmatitic Gangdese arc rocks exposed in southeastern Tibet indicate that magmatic reworking affected the southern Lhasa terrane by Oligocene time [Zhang *et al.*, 2014].

7.4. Oligocene-Miocene Tectonics and Kailas Basin Development

Following cessation of Gangdese arc magmatism circa 38 Ma, there is no record of suture zone deformation and metamorphism prior to initial Kailas Formation deposition during late Oligocene time (Figure 13a). Between 38 and 28 Ma, upper crustal shortening and corresponding crustal thickening was localized farther to the south within the Tethyan Himalayan thrust belt (Figure 14d), driving Eocene-Oligocene Himalayan metamorphism [e.g., Hodges, 2000; Aikman *et al.*, 2008]. The timing of thrusting in the Tethyan Himalayan thrust belt is consistent with prograde to peak metamorphic conditions [Hacker *et al.*, 1998; Lee *et al.*, 2000, 2004] and migmatite generation (35–32 Ma) in Greater Himalayan rocks that core North Himalayan domes (Figure 2) [e.g., Lee and Whitehouse, 2007].

During Oligocene-Miocene time, Kailas Formation strata were deposited in buttress unconformity atop Gangdese arc rocks along the southern margin of the Lhasa terrane [Leary *et al.*, 2016] (Figures 2, 3, and 13a), north of the Xigaze fore-arc basin. Detrital zircons in the Kailas Formation record at least partial derivation from the Gangdese magmatic arc to the north (Figure 9). The lower part of the Kailas Formation records a brief period (likely <3 Myr at a given locality) of N-S extensional reactivation of the Yarlung suture in response to rollback and breakoff of subducted Greater Indian lithosphere relative to Indian and Asian crust, possibly driven by northward motion of the subduction interface relative to the upper mantle [DeCelles *et al.*, 2011; Leary *et al.*, 2016; DeCelles *et al.*, 2016a].

The Miocene Great Counter Thrust system (GCT) initiated along the Yarlung suture during the late stages of Kailas Formation deposition (<23 Ma), as evidenced by a transition to southerly provenance during this time [DeCelles *et al.*, 2011; Carrapa *et al.*, 2014; Leary *et al.*, 2016]. We interpret that renewed underthrusting of India following Greater Indian slab rollback and breakoff caused the switch from Kailas basin extension to GCT contraction, consistent with the model presented by DeCelles *et al.* [2011] (Figure 14). The return to underthrusting possibly drove exhumation of Gangdese arc rocks to the west and east of the Lopu Range, which cooled below biotite $^{40}\text{Ar}/^{39}\text{Ar}$ closure temperature (~320°C) by ~20 Ma [Sanchez *et al.*, 2013] and below zircon He closure (~180°C) by 19.6 ± 0.4 Ma (sample 62011PK6; Figure 3), respectively. Statistically indistinguishable cooling ages for the $^{40}\text{Ar}/^{39}\text{Ar}$ biotite and zircon (U-Th)/He systems, differing in closure temperature by ~140°C, suggest rapid cooling. Remarkably, Gangdese arc rocks were at the surface during deposition of the Oligocene-Miocene Kailas Formation and were therefore buried to depths sufficient to reset the $^{40}\text{Ar}/^{39}\text{Ar}$ biotite and zircon-He systems (>320°C) and then cooled to <180°C within a period of ~5 Myr. Previous models that seek to explain early Miocene cooling of Gangdese arc rocks involve exhumation in the hanging wall of a blind thrust related to the GCT [Sanchez *et al.*, 2013] or exhumation related to regional-scale enhanced rock driven by renewed Indian underthrusting [Carrapa *et al.*, 2014] (Figure 14). The Lopukangri and Rujiao normal faults are not plausible drivers, as the samples were in their hanging walls (Figure 3).

7.5. Miocene to Recent Orogen-Parallel Extension

The GCT is cut by the Rujiao and Lopukangri normal faults, which are related to Miocene-recent orogen-parallel (E-W) extension of southern Tibet. One leucogranite dike (7112AL2) cuts a footwall splay of the Lopukangri fault (Figure 3), providing an ~16 Ma minimum age of extension onset. The other leucogranites in the Lopu Range, confined to the footwalls of the Lopukangri and Rujiao faults, also crystallized at ~16 Ma ($n = 6$; Figures 8c and 13a). Whether leucogranites were generated prior to extension onset—potentially

localizing normal faults—or by decompression melting during extension remains unclear. Whatever the case, thermal and melt weakening resulting from leucogranite intrusion probably facilitated orogen-parallel extension in the Lopus Range [Sundell *et al.*, 2013].

Leucogranites in the Lopus Range contain abundant xenocrystic zircon cores with Paleoproterozoic–Cenozoic ages (Figure 8c). Most xenocrystic zircon cores are between ~32–47 Ma, 115–183 Ma, 350–590 Ma, and 0.75–2.5 Ga. The youngest cores have ages between 17 and 25 Ma and U/Th values up to ~35, overlapping in age with older North Himalayan leucogranites that are predominately exposed in the North Himalayan domes (Figure 2). We interpret that these zircons crystallized in a hot, potentially molten layer in Tibetan crust during late Eocene time, possibly extending from the North Himalayan domes to the Yarlung suture zone, which formed due to prior crustal thickening. The remaining xenocrystic zircons might have been derived from Lhasa terrane and Gangdese arc rocks, including the 210–165 Ma zircons for which there is no known Tethyan Himalaya sequence or Greater Himalaya sequence source (Figure 9). The presence of Lhasa terrane rocks beneath the Yarlung suture zone during Miocene time can be explained by northward translation of suture zone rocks across the GCT but is also consistent with southward ductile flow of the lower crust (Figure 1) [e.g., Beaumont *et al.*, 2001]. Leucogranites that intrude the Ayilari Mountains, ~200 km to the northwest of Mount Kailas (Figure 1), also include xenocrystic zircon cores with ages that suggest the presence of Gangdese arc rocks at depth beneath the Indus suture zone [Zhang *et al.*, 2011].

Zircon (U–Th)/He ages from the Lopus Range horst block are between 8.5 and 6.0 Ma ($n = 6$) with one older age of ~12 Ma (Figure 13a). Therefore, the majority of the sampled region (Figures 3 and 11) cooled below ~180°C between 9 and 6 Ma (Figure 13b). These rocks previously cooled below $^{40}\text{Ar}/^{39}\text{Ar}$ white mica closure temperature (~350°C) between 38 and 27 Ma (Figure 13b) [Laskowski *et al.*, 2016]. Based on these data and assumption of a minimum 30°C/km geothermal gradient, up to 6 km of pre-6 Ma exhumation and an equivalent maximum magnitude of post-6 Ma exhumation is inferred (Figure 13b). Substantially higher transient geothermal gradients can be produced in rifts during extension, resulting in condensed footwall isotherms [e.g., Sundell *et al.*, 2013]. The timing of extension is consistent with the findings of numerous investigations of generally N–S oriented rifts across the southern and central Tibetan Plateau, revealing middle Miocene extension onset followed by late Miocene–Pliocene acceleration of exhumation [Sundell *et al.*, 2013; Styron *et al.*, 2015].

A number of local, regional, or orogen-scale drivers can explain the onset and acceleration of E–W extension in Tibet. The apparent synchronicity of these events across the southern Tibetan Plateau, however, points to an extrinsic cause. We favor the interpretation that the onset of extension resulted from renewed, low-angle underthrusting of Indian continental lithosphere following mid-Miocene Greater Indian rollback and breakoff (Figures 14d and 14e), evidenced by tomographic anomalies and lithospheric structure beneath India and Tibet [Van der Voo *et al.*, 1999; DeCelles *et al.*, 2002]. If our interpretation that the Great Counter Thrust system (GCT) is related to the return to Indian underthrusting is correct, then the age of the synkinematic upper Kailas Formation (~23 Ma) [Leary *et al.*, 2016] provides an indirect timing constraint. Indian underthrusting likely increased the magnitude of N–S compressive stress through increased coupling at the subduction interface, driving crustal thickening (e.g., the GCT) and regional-scale rock uplift related to the buoyancy contrast between continental lithosphere and upper mantle rocks. Crosscutting relationships in the Lopus Range indicate initiation of E–W extension by circa 16 Ma. It is also possible that the onset of E–W extension coincided with or was the result of a change in plate boundary conditions in Southeast Asia, possibly involving a decrease in E–W compressive stress related to early Miocene subduction initiation between the Eurasia and Philippine Sea plates [von Hagke *et al.*, 2016], allowing for eastward crustal extrusion accommodated by extension in southern Tibet [Taylor and Yin, 2009]. Late Miocene to Pliocene extension acceleration [Sundell *et al.*, 2013] requires an additional driver, which we interpret was the attainment of a critical gravitational potential energy through crustal thickening. If Indian underthrusting thickened Tibetan crust beyond the threshold, then a northward sweep of extension acceleration tracking the frontal Indian slab should have occurred [Kapp and Guynn, 2004]. Thermal modeling of the Lunggar Rift [Styron *et al.*, 2015] and orogen-scale observations from a compilation of rift timing constraints across the southern Tibetan Plateau [Sundell *et al.*, 2013] are consistent with this explanation.

8. Conclusions

The Lopus Range records development of the Lhasa terrane convergent margin and subsequent Himalayan–Tibetan orogenesis since Jurassic time. U–Pb and zircon (U–Th)/He data from a hornblende–plagioclase–epidote

paragneiss in a tectonic sliver of ophiolitic mélange were interpreted to record Late Jurassic or Early Cretaceous subduction initiation. Serpentine-matrix mélange cooled below zircon (U-Th)/He closure ($\sim 180^\circ\text{C}$) at ~ 107 Ma, likely recording fore-arc extension prior to basal Xigaze fore-arc deposition at ~ 97 Ma. The provenance linkage between the Gangdese arc and Xigaze fore-arc—deposited unconformably atop ophiolitic rocks—indicates that the ophiolitic rocks were in a suprasubduction zone position by Late Cretaceous time. Early-middle Eocene Gangdese arc rocks intrude subduction-accretion mélange in the southern Lhasa terrane, indicating southward subduction zone migration and/or steep subduction following Paleocene-Eocene collision onset. The Great Counter Thrust is interpreted to record renewed Indian underthrusting following rollback and breakoff circa 23 Ma. Leucogranites that intrude the Lopu Range are ~ 16 Ma, including one sample that cuts a footwall splay of the Lopukangri fault, providing a minimum age for the onset of E-W extension in southern Tibet. Meta-Tethyan rocks and leucogranites in the footwalls of the Lopukangri and Rujiao range-bounding normal faults cooled below $\sim 180^\circ\text{C}$ between 12 and 6 Ma, likely due to tectonic exhumation related to Miocene orogen-parallel ($\sim$ E-W) extension of southern Tibet.

The Paleocene-Pliocene tectonics of Tibet and the Himalaya are punctuated by two episodes of rollback and underthrusting (Figure 14) that are recorded by the geology of the Lopu Range (Figure 13a). Integration of Lopu Range geologic data with orogen-scale tectonic data suggests that periodic underthrusting and rollback events controlled deformation along the Yarlung suture throughout India-Asia collision. The tectonic model presented here (Figure 14) explains key events in the tectonic evolution of the Tibetan-Himalayan orogenic system, especially the transition between alternating phases of contraction and extension.

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References

- Aikman, A. B., T. M. Harrison, and L. Ding (2008), Evidence for early (>44 Ma) Himalayan crustal thickening, Tethyan Himalaya, southeastern Tibet, *Earth Planet. Sci. Lett.*, *274*(1), 14–23.
- Aitchison, J. C., A. M. Davis, and H. Luo (2002), New constraints on the India-Asia collision: The lower Miocene Gangrinboche conglomerates, Yarlung Tsangpo suture zone, SE Tibet, *J. Asian Earth Sci.*, *21*(3), 251–263.
- Aitchison, J. C., J. R. Ali, and A. M. Davis (2007), When and where did India and Asia collide?, *J. Geophys. Res.*, *112*, B05423, doi:10.1029/2006JB004706.
- An, W., X. Hu, E. Garzanti, M. K. BouDagher-Fadel, J. Wang, and G. Sun (2014), Xigaze forearc basin revisited (South Tibet): Provenance changes and origin of the Xigaze Ophiolite, *Geol. Soc. Am. Bull.*, *126*(11–12), 1595–1613, doi:10.1130/B31020.1.
- Beaumont, C., R. A. Jamieson, M. H. Nguyen, and B. Lee (2001), Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation, *Nature*, *414*(6865), 738–742, doi:10.1038/414738a.
- Beaumont, C., R. A. Jamieson, J. P. Butler, and C. J. Warren (2009), Crustal structure: A key constraint on the mechanism of ultra-high-pressure rock exhumation, *Earth Planet. Sci. Lett.*, *287*(1–2), 116–129, doi:10.1016/j.epsl.2009.08.001.
- Black, L. P., S. L. Kamo, C. M. Allen, D. W. Davis, and J. N. Aleinikoff (2004), Improved $^{206}\text{Pb}/^{238}\text{U}$ microprobe geochronology by the monitoring of a trace-element-related matrix effect: SHRIMP, ID-TIMS, ELA-ICP-MS and oxygen isotope documentation for a series of zircon standards, *Chem. Geol.*, *205*, 114–140, doi:10.1016/j.chemgeo.2004.01.003.
- Burchfiel, B. C., C. Zhiliang, K. V. Hodges, L. Yiping, L. H. Royden, D. Changrong, and A. Xujiene (1992), *The South Tibetan Detachment System, Himalayan Orogen: Extension Contemporaneous With and Parallel to Shortening in a Collisional Mountain Belt*, Geol. Soc. Am., Boulder, Colo.
- Burg, J. P., and G. M. Chen (1984), Tectonics and structural zonation of southern Tibet, China, *Nature*, *311*(5983), 219–223.
- Burg, J. P., M. Guiraud, G. M. Chen, and G. C. Li (1984), Himalayan metamorphism and deformations in the North Himalayan Belt (southern Tibet, China), *Earth Planet. Sci. Lett.*, *69*, 391–400.
- Burg, J. P., A. Leyreloup, J. Girardeau, and G. M. Chen (1987), Structure and metamorphism of a tectonically thickened continental crust: The Yalu Tsangpo suture zone (Tibet), *Philos. Trans. R. Soc. London, Ser. A*, *321*(1557), 67–86.
- Burke, K., J. F. Dewey, and W. Kidd (1977), World distribution of sutures—The sites of former oceans, *Tectonophysics*, *40*(1), 69–99.
- Cai, F., L. Ding, R. J. Leary, H. Wang, Q. Xu, L. Zhang, and Y. Yue (2012), Tectonostratigraphy and provenance of an accretionary complex within the Yarlung-Zangpo suture zone, southern Tibet: Insights into subduction-accretion processes in the Neo-Tethys, *Tectonophysics*, *574*, 181–192, doi:10.1016/j.tecto.2012.08.016.
- Carrapa, B., D. A. Orme, P. G. DeCelles, P. Kapp, M. A. Cosca, and R. Waldrip (2014), Miocene burial and exhumation of the India-Asia collision zone in southern Tibet: Response to slab dynamics and erosion, *Geology*, *42*(5), 443–446, doi:10.1130/G35350.1.
- Chan, G. H. N., J. C. Aitchison, Q. G. Crowley, M. S. A. Horstwood, M. P. Searle, R. R. Parrish, and J. S.-L. Chan (2015), U-Pb zircon ages for Yarlung Tsangpo suture zone ophiolites, southwestern Tibet and their tectonic implications, *Gondwana Res.*, *27*(2), 719–732, doi:10.1016/j.gr.2013.06.016.
- Chemenda, A. I., J.-P. Burg, and M. Mattauer (2000), Evolutionary model of the Himalaya-Tibet system: Geopoe—Based on new modelling, geological and geophysical data, *Earth Planet. Sci. Lett.*, *174*(3–4), 397–409, doi:10.1016/S0012-821X(99)00277-0.
- Clift, P. D., P. Vannucchi, and J. P. Morgan (2009), Crustal redistribution, crust-mantle recycling and Phanerozoic evolution of the continental crust, *Earth Sci. Rev.*, *97*(1), 80–104, doi:10.1016/j.earscirev.2009.10.003.
- Davis, A. M., J. C. Aitchison, H. L. Badengzhu, and S. Zyabrev (2002), Paleogene island arc collision-related conglomerates, Yarlung-Tsangpo suture zone, Tibet, *Sediment. Geol.*, *150*(3–4), 247–273.
- DeCelles, P. G., D. M. Robinson, and G. Zandt (2002), Implications of shortening in the Himalayan fold-thrust belt for uplift of the Tibetan Plateau, *Tectonics*, *21*(6), 12–1–12–25, doi:10.1029/2001TC001322.
- DeCelles, P. G., P. Kapp, J. Quade, and G. E. Gehrels (2011), Oligocene-Miocene Kailas basin, southwestern Tibet: Record of postcollisional upper-plate extension in the Indus-Yarlung suture zone, *Geol. Soc. Am. Bull.*, *123*(7–8), 1337–1362, doi:10.1130/B30258.1.
- DeCelles, P. G., P. Kapp, G. E. Gehrels, and L. Ding (2014), Paleocene-Eocene foreland basin evolution in the Himalaya of southern Tibet and Nepal: Implications for the age of initial India-Asia collision, *Tectonics*, *33*, 824–829, doi:10.1002/2014TC003522.

- DeCelles, P. G., G. Gehrels, J. Quade, B. LaReau, and M. Spurlin (2000), Tectonic implications of U-Pb zircon ages of the Himalayan orogenic belt in Nepal, *Science*, 288(5465), 497.
- DeCelles, P. G., I. Castenada, B. Carrapa, J. Liu, J. Quade, R. Leary, and L. Zhang (2016a), Oligocene-Miocene great lakes in the India-Asia collision zone, *Basin Res.*, doi:10.1111/bre.12217.
- DeCelles, P. G., B. Carrapa, G. E. Gehrels, T. Chakraborty, P. Ghosh, and G. Jehle (2016b), Structure, stratigraphy, and kinematic history of the eastern Himalayan thrust belt, Arunachal Pradesh, India, *Tectonics*, doi:10.1002/2016TC004298.
- Ding, L., P. Kapp, and X. Wan (2005), Paleocene-Eocene record of ophiolite obduction and initial India-Asia collision, south central Tibet, *Tectonics*, TC3001, doi:10.1029/2004TC001729.
- Donaldson, D. G., A. A. G. Webb, C. A. Menold, A. R. C. Kylander-Clark, and B. R. Hacker (2013), Petrochronology of Himalayan ultrahigh-pressure eclogite, *Geology*, 41(8), 835–838, doi:10.1130/G33699.1.
- Draganits, E., B. Grasemann, W. Frank, C. Miller, and G. Wiesmayr (1998), The sedimentary protoliths of the HHC in the Chamba-Lahaul Area (NW-Himalayas, India) 13th Himalaya Karakorum Tibet Workshop, Peshawar, 20–22 April 1998, Geological Bulletin University of Peshawar, Special Issue, 31, 58–60.
- Dunkl, I., et al. (2011), Metamorphic evolution of the Tethyan Himalayan flysch in SE Tibet, in *Growth and Collapse of the Tibetan Plateau*, *Geol. Soc. Spec. Publ.*, vol. 353, edited by R. Gloaguen and L. Ratschbacher, pp. 45–69.
- Dürr, S. B. (1996), Provenance of Xigaze fore-arc basin clastic rocks (Cretaceous, south Tibet), *Geol. Soc. Am. Bull.*, 108(6), 669–684, doi:10.1130/0016-7606(1996)108<0669:POXFAB>2.3.CO;2.
- Einsele, G., B. Liu, S. Dürr, W. Frisch, G. Liu, H. P. Luterbacher, L. Ratschbacher, W. Ricken, J. Wendt, and A. Wetzel (1994), The Xigaze forearc basin: Evolution and facies architecture (Cretaceous, Tibet), *Sediment. Geol.*, 90(1), 1–32.
- England, P. C., and A. B. Thompson (1984), Pressure temperature time paths of regional metamorphism: I. Heat transfer during the evolution of regions of thickened continental crust, *J. Petrol.*, 25(4), 894–928.
- Epard, J.-L., and A. Steck (2008), Structural development of the Tso Moriri ultra-high pressure nappe of the Ladakh Himalaya, *Tectonophysics*, 451(1–4), 242–264, doi:10.1016/j.tecto.2007.11.050.
- Gaetani, M., and E. Garzanti (1991), Multicyclic history of the northern India continental margin (northwestern Himalaya), *AAPG Bull.*, 75(9), 1427–1446.
- Gansser, A. (1964), in *Geology of the Himalayas*, edited by L. U. De Sitter, Interscience, London.
- Garzanti, E. (1999), Stratigraphy and sedimentary history of the Nepal Tethys Himalaya passive margin, *J. Asian Earth Sci.*, 17(5–6), 805–827.
- Garzanti, E., P. G. DeCelles, D. G. Hodkinson, T. P. Ojha, and B. N. Upreti (2003), East-west extension and Miocene environmental change in the southern Tibetan plateau: Thakkhola graben, central Nepal, *Geol. Soc. Am. Bull.*, 115(1), 3–20.
- Gehrels, G. E., V. Valencia, and A. Pullen (2006), Detrital zircon geochronology by Laser-Ablation Multicollector ICPMS at the Arizona LaserChron Center, in *Geochronology: Emerging Opportunities, Paleontology Society Short Course, Paleontol. Soc. Pap.*, vol. 11, edited by T. Loszewski and W. Huff, pp. 10, Paleontological Society, Boulder, Colo.
- Gehrels, G. E., V. Valencia, and J. Ruiz (2008), Enhanced precision, accuracy, efficiency, and spatial resolution of U-Pb ages by laser ablation–multicollector–inductively coupled plasma–mass spectrometry, *Geochim. Geophys. Geosyst.*, 9, Q03017, doi:10.1029/2007GC001805.
- Gehrels, G., et al. (2011), Detrital zircon geochronology of pre-Tertiary strata in the Tibetan-Himalayan orogen, *Tectonics*, 30, TC5016, doi:10.1029/2011TC002868.
- Girardeau, J., J. Marcoux, and Z. Yougong (1984), Lithologic and tectonic environment of the Xigaze ophiolite (Yarlung Zangbo suture zone, Southern Tibet, China), and kinematics of its emplacement, *Eclogae Geol. Helv.*, 77(1), 153–170.
- Guillot, S., G. Mahéo, J. de Sigoyer, K. H. Hattori, and A. Pecher (2008), Tethyan and Indian subduction viewed from the Himalayan high- to ultrahigh-pressure metamorphic rocks, *Tectonophysics*, 451(1–4), 225–241, doi:10.1016/j.tecto.2007.11.059.
- Guilmette, C., R. Hébert, C. Wang, and M. Villeneuve (2009), Geochemistry and geochronology of the metamorphic sole underlying the Xigaze ophiolite, Yarlung Zangbo Suture Zone, south Tibet, *Lithos*, 112, 149–162, doi:10.1016/j.lithos.2009.05.027.
- Guilmette, C., R. Hébert, J. Dostal, A. Indares, T. Ullrich, É. Bédard, and C. Wang (2012), Discovery of a dismembered metamorphic sole in the Saga ophiolitic mélange, South Tibet: Assessing an Early Cretaceous disruption of the Neo-Tethyan supra-subduction zone and consequences on basin closing, *Gondwana Res.*, 22(2), 398–414, doi:10.1016/j.gr.2011.10.012.
- Hacker, B. R., J. Lee, and D. B. Root (1998), Middle Miocene shortening in southern Tibet: II. Petrology reveals a southward-increasing pressure gradient Geological Society of America Abstracts with Programs, 30, 270.
- Harris, N., and J. Massey (1994), Decompression and anatexis of Himalayan metapelites, *Tectonics*, 13(6), 1537–1546, doi:10.1029/94TC01611.
- Harrison, T. M., O. M. Lovera, and M. Grove (1997a), New insights into the origin of two contrasting Himalayan granite belts, *Geology*, 25(10), 899–902, doi:10.1130/0091-7613(1997)025<0899:NIITOO>2.3.CO;2.
- Harrison, T. M., F. J. Ryerson, P. Le Fort, A. Yin, O. M. Lovera, and E. J. Catlos (1997b), A late Miocene-Pliocene origin for the central Himalayan inverted metamorphism, *Earth Planet. Sci. Lett.*, 146(1), E1–E7.
- Harrison, T. M., M. Grove, O. M. Lovera, and E. J. Catlos (1998), A model for the origin of Himalayan anatexis and inverted metamorphism, *J. Geophys. Res.*, 103(B11), 27,017–27,032, doi:10.1029/98JB02468.
- Hebei Province Geologic Survey (2002), 1:250000 Mapsheet of Saga County (H45 C 003001) Report of Regional Geological Survey, Institute of Regional Geological and Mineral Survey, Hebei Province, China.
- Hébert, R., R. Bezaud, C. Guilmette, J. Dostal, C. S. Wang, and Z. F. Liu (2012), The Indus–Yarlung Zangbo ophiolites from Nanga Parbat to Namche Barwa syntaxes, southern Tibet: First synthesis of petrology, geochemistry, and geochronology with incidences on geodynamic reconstructions of Neo-Tethys, *Gondwana Res.*, 22(2), 377–397, doi:10.1016/j.gr.2011.10.013.
- Heim, A., and A. Gansser (1939), *Central Himalaya: Geological Observations of the Swiss Expedition 1936*, Hindustan, Delhi.
- Hintersberger, E., R. C. Thiede, M. R. Strecker, and B. R. Hacker (2010), East-west extension in the NW Indian Himalaya, *Geol. Soc. Am. Bull.*, 122(9–10), 1499–1515, doi:10.1130/B26589.1.
- Hodges, K. V. (2000), Tectonics of the Himalaya and southern Tibet from two perspectives, *Geol. Soc. Am. Bull.*, 112(3), 324–350, doi:10.1130/0016-7606(2000)112<324:TOTHAS>2.0.CO;2.
- Hodges, K., R. Parrish, and M. Searle (1996), Tectonic evolution of the central Annapurna range, Nepalese Himalayas, *Tectonics*, 15(6), 1264–1291.
- Hourigan, J. K., P. W. Reiners, and M. T. Brandon (2005), U-Th zonation-dependent alpha-ejection in (U-Th)/He chronometry, *Geochim. Cosmochim. Acta*, 69(13), 3349–3365, doi:10.1016/j.gea.2005.01.024.
- Hu, X., J. Wang, M. BouDagher-Fadel, and E. Garzanti (2016), New insights into the timing of the India–Asia collision from the Paleogene Quxia and Jialazi formations of the Xigaze forearc basin, South Tibet, *Gondwana Res.*, 32, 76–92.
- Huang, W., D. J. J. Van Hinsbergen, M. Maffione, D. A. Orme, G. Dupont-Nivet, C. Guilmette, L. Ding, Z. Guo, and P. Kapp (2015), Lower Cretaceous Xigaze ophiolites formed in the Gangdese forearc: Evidence from paleomagnetism, sediment provenance, and stratigraphy, *Earth Planet. Sci. Lett.*, 415, 142–153, doi:10.1016/j.epsl.2015.01.032.

- Kapp, P., and J. H. Guynn (2004), Indian punch rifts Tibet, *Geology*, 32(11), 993–996, doi:10.1130/G20689.1.
- Kapp, P., P. G. DeCelles, A. L. Leier, J. M. Fabijanic, and S. He (2007), The Gangdese retroarc thrust belt revealed, *GSA Today*, 17(7), 4–9, doi:10.1130/GSAT01707A.1.
- Kapp, P., M. Taylor, D. Stockli, and L. Ding (2008), Development of active low-angle normal fault systems during orogenic collapse: Insight from Tibet, *Geology*, 36(1), 7–10, doi:10.1130/G24054A.1.
- Kohn, M. J. (2014), Himalayan metamorphism and its tectonic implications, *Annu. Rev. Earth Planet. Sci.*, 42, 381–419, doi:10.1146/annurev-earth-060313-055005.
- Larson, K. P., L. Godin, W. J. Davis, and D. W. Davis (2010), Out-of-sequence deformation and expansion of the Himalayan orogenic wedge: Insight from the Changgo culmination, south central Tibet, *Tectonics*, 29, TC4013, doi:10.1029/2008TC002393.
- Laskowski, A. K., P. Kapp, J. D. Vervoort, and L. Ding (2016), High-pressure Tethyan Himalaya rocks along the India-Asia suture zone in southern Tibet, *Lithosphere*, 8(5), 574–582, doi:10.1130/L544.1.
- Le Fort, P. (1975), Himalayas: The collided range. Present knowledge of the continental arc, *Am. J. Sci.*, 275-A, 1–44.
- Le Fort, P. (1986), Metamorphism and magmatism during the Himalayan collision, *Geol. Soc. London, Spec. Publ.*, 19(1), 159–172, doi:10.1144/GSL.SP.1986.019.01.08.
- Leary, R., D. A. Orme, A. K. Laskowski, P. G. DeCelles, P. Kapp, B. Carrapa, and M. Dettinger (2016), Along-strike diachroneity in deposition of the Kailas Formation in central southern Tibet: Implications for Indian slab dynamics, *Geosphere*, 12(4), 1198–1223, doi:10.1130/GES01325.1.
- Lee, H.-Y., S.-L. Chung, C.-H. Lo, J. Ji, T.-Y. Lee, Q. Qian, and Q. Zhang (2009), Eocene Neotethyan slab breakoff in southern Tibet inferred from the Linzizong volcanic record, *Tectonophysics*, 477(1), 20–35, doi:10.1016/j.tecto.2009.02.031.
- Lee, J., and M. J. Whitehouse (2007), Onset of mid-crustal extensional flow in southern Tibet: Evidence from U/Pb zircon ages, *Geology*, 35(1), 45–48, doi:10.1130/G22842A.1.
- Lee, J., B. R. Hacker, W. S. Dinklage, Y. Wang, P. Gans, A. Calvert, J. Wan, W. Chen, A. E. Blythe, and W. McClellands (2000), Evolution of the Kangmar Dome, southern Tibet: Structural, petrologic, and thermochronologic constraints, *Tectonics*, 19(5), 872–895, doi:10.1029/1999TC001147.
- Lee, J., B. R. Hacker, and Y. Wang (2004), Evolution of North Himalayan gneiss domes: Structural and metamorphic studies in Mabja Dome, southern Tibet, *J. Struct. Geol.*, 26(12), 2297–2316, doi:10.1016/j.jsg.2004.02.013.
- Liu, G., and G. Einsele (1994), Sedimentary history of the Tethyan basin in the Tibetan Himalayas, *Geol. Rundsch.*, 83(1), 32–61.
- Liu, X.-C., F.-Y. Wu, L.-J. Yu, Z.-C. Liu, W.-Q. Ji, and J.-G. Wang (2016), Emplacement age of leucogranite in the Kampa Dome, southern Tibet, *Tectonophysics*, 667, 163–175.
- Maffione, M., D. J. J. van Hinsbergen, L. M. T. Koornneef, C. Guilmette, K. Hodges, N. Borneman, W. Huang, L. Ding, and P. Kapp (2015), Forearc hyperextension dismembered the south Tibetan ophiolites, *Geology*, 43(6), 475–478, doi:10.1130/G36472.1.
- Malpas, J., M. F. Zhou, P. T. Robinson, and P. H. Reynolds (2003), Geochemical and geochronological constraints on the origin and emplacement of the Yarlung Zangbo ophiolites, Southern Tibet, *Geol. Soc. London Spec. Publ.*, 218(1), 191–206, doi:10.1144/GSL.SP.2003.218.01.11.
- McCallister, A. T., M. H. Taylor, M. A. Murphy, R. H. Styrone, and D. F. Stockli (2014), Thermochronologic constraints on the late Cenozoic exhumation history of the Gurla Mandhata metamorphic core complex, Southwestern Tibet, *Tectonics*, 33, 1–23, doi:10.1002/2013TC003302.
- Moores, E. M. (1981), Ancient suture zones within continents, *Science*, 213(4503), 41–46, doi:10.1126/science.213.4503.41.
- Murphy, M. A., and P. Copeland (2005), Transtensional deformation in the central Himalaya and its role in accommodating growth of the Himalayan orogen, *Tectonics*, 24, TC4012, doi:10.1029/2004TC001659.
- Murphy, M. A., V. Sanchez, and M. H. Taylor (2010), Syncollisional extension along the India–Asia suture zone, south-central Tibet: Implications for crustal deformation of Tibet, *Earth Planet. Sci. Lett.*, 290(3–4), 233–243, doi:10.1016/j.epsl.2009.11.046.
- Myrow, P. M., N. C. Hughes, J. W. Goodge, C. M. Fanning, I. S. Williams, S. Peng, O. N. Bhargava, S. K. Parcha, and K. R. Pogue (2010), Extraordinary transport and mixing of sediment across Himalayan central Gondwana during the Cambrian–Ordovician, *Geol. Soc. Am. Bull.*, 122(9–10), 1660–1670, doi:10.1130/B30123.1.
- Noble, S. R., and M. P. Searle (1995), Age of crustal melting and leucogranite formation from U–Pb zircon and monazite dating in the western Himalaya, Zaskar, India, *Geology*, 23(12), 1135, doi:10.1130/0091-7613(1995)023<1135:AOCMAL>2.3.CO;2.
- Orme, D. A., and A. K. Laskowski (2016), Basin analysis of the Albian–Santonian Xigaze forearc, Lazi region, south-central Tibet, *J. Sediment. Res.*, 86, 1–20, doi:10.2110/jsr.2016.59.
- Orme, D. A., B. Carrapa, and P. Kapp (2015), Sedimentology, provenance and geochronology of the upper Cretaceous–lower Eocene western Xigaze forearc basin, southern Tibet, *Basin Res.*, 27(4), 387–411, doi:10.1111/bre.12080.
- Paces, J. B., and J. D. Miller (1993), Precise U–Pb ages of Duluth complex and related mafic intrusions, northeastern Minnesota: Geochronological insights to physical, petrogenetic, paleomagnetic, and tectonomagmatic processes associated with the 1.1 Ga mid-continent rift system, *J. Geophys. Res.*, 98(B8), 13,997–14,013, doi:10.1029/93JB01159.
- Pullen, A., P. Kapp, P. G. DeCelles, G. E. Gehrels, and L. Ding (2011), Cenozoic anatexis and exhumation of Tethyan Sequence rocks in the Xiao Gurla Range, Southwest Tibet, *Tectonophysics*, 501(1–4), 28–40, doi:10.1016/j.tecto.2011.01.008.
- Quidelleur, X., M. Grove, O. M. Lovera, T. M. Harrison, A. Yin, and F. J. Ryerson (1997), Thermal evolution and slip history of the Renbu Zedong Thrust, southeastern Tibet, *J. Geophys. Res.*, 102(B2), 2659–2679, doi:10.1029/96JB02483.
- Ratschbacher, L., W. Frisch, G. H. Liu, and C. S. Chen (1994), Distributed deformation in southern and western Tibet during and after the India–Asia collision, *J. Geophys. Res.*, 99(B10), 19,917–19,945, doi:10.1029/94JB00932.
- Reiners, P. W. (2005), Zircon (U–Th)/He thermochronometry, *Rev. Mineral. Geochem.*, 58, 151–179.
- Reiners, P. W., T. L. Spell, S. Nicolescu, and K. A. Zanetti (2004), Zircon (U–Th)/He thermochronometry: He diffusion and comparisons with (40)Ar/(39)Ar dating, *Geochim. Cosmochim. Acta*, 68(8), 1857–1887, doi:10.1016/j.gca.2003.10.021.
- Rubatto, D., I. S. Williams, and I. S. Buick (2001), Zircon and monazite response to prograde metamorphism in the Reynolds Range, central Australia, *Contrib. Mineral. Petrol.*, 140(4), 458–468.
- Ryan, W. B. F., et al. (2009), Global multi-resolution topography synthesis, *Geochem. Geophys. Geosyst.*, 10, Q03014, doi:10.1029/2008GC002332.
- Sanchez, V. I., M. A. Murphy, A. C. Robinson, T. J. Lapen, and M. T. Heizler (2013), Tectonic evolution of the India–Asia suture zone since Middle Eocene time, Lopukangri area, south-central Tibet, *J. Asian Earth Sci.*, 62(C), 205–220, doi:10.1016/j.jseas.2012.09.004.
- Schärer, U., R.-H. Xu, and C. J. Allègre (1984), UPb geochronology of Gangdese (Transhimalaya) plutonism in the Lhasa–Xigaze region, Tibet, *Earth Planet. Sci. Lett.*, 69(2), 311–320, doi:10.1016/0012-821X(84)90190-0.
- Schärer, U., R.-H. Xu, and C. J. Allègre (1986), U–(Th)–Pb systematics and ages of Himalayan leucogranites, South Tibet, *Earth Planet. Sci. Lett.*, 77(1), 35–48, doi:10.1016/0012-821X(86)90130-5.

- Schmitz, M. D., and S. A. Bowring (2001), U-Pb zircon and titanite systematics of the Fish Canyon Tuff: An assessment of high-precision U-Pb geochronology and its application to young volcanic rocks, *Geochim. Cosmochim. Acta*, 65(15), 2571–2587.
- Searle, M. P. (1999), Emplacement of Himalayan leucogranites by magma injection along giant sill complexes: Examples from the Cho Oyu, Gyachung Kang and Everest leucogranites (Nepal Himalaya), *J. Asian Earth Sci.*, 17(5–6), 773–783, doi:10.1016/S1367-9120(99)00020-6.
- Searle, M. P., and L. Godin (2003), The South Tibetan detachment and the Manaslu Leucogranite: A structural reinterpretation and restoration of the Annapurna-Manaslu Himalaya, Nepal, *J. Geol.*, 111(5), 505–523, doi:10.1086/376763.
- Searle, M. P., R. R. Parrish, K. V. Hodges, A. Hurford, M. W. Ayres, and M. J. Whitehouse (1997), Shisha Pangma leucogranite, South Tibetan Himalaya: Field relations, geochemistry, age, origin, and emplacement, *J. Geol.*, 105, 295–318.
- Searle, M. P., et al. (1987), The closing of Tethys and the tectonics of the Himalaya, *GSA Bulletin*, 98(6), 678, doi:10.1130/0016-7606(1987)98<678:TCOTAT>2.0.CO;2.
- Spencer, D. A., S. Tonarini, and U. Pognante (1995), Geochemical and Sr-Nd isotopic characterization of Higher Himalayan eclogites (and associated metabasites), *Eur. J. Mineral.*, 7(1), 89–102.
- Stacey, J. S., and J. D. Kramers (1975), Approximation of terrestrial lead isotope evolution by a two-stage model, *Earth Planet. Sci. Lett.*, 26, 207–221.
- Styron, R., M. Taylor, and K. Sundell (2015), Accelerated extension of Tibet linked to the northward underthrusting of Indian crust, *Nat. Geosci.*, 8(2), 131–134, doi:10.1038/ngeo2336.
- Sundell, K. E., M. H. Taylor, R. H. Styron, D. F. Stockli, P. Kapp, C. Hager, D. Liu, and L. Ding (2013), Evidence for constriction and Pliocene acceleration of east-west extension in the North Lunggar rift region of west central Tibet, *Tectonics*, 32, 1–26, doi:10.1002/tect.20086.
- Taylor, M., and A. Yin (2009), Active structures of the Himalayan-Tibetan orogen and their relationships to earthquake distribution, contemporary strain field, and Cenozoic volcanism, *Geosphere*, 5(3), 199–214, doi:10.1130/GES00217.1.
- Thiede, R. C., J. R. Arrowsmith, B. Bookhagen, M. McWilliams, E. R. Sobel, and M. R. Strecker (2006), Dome formation and extension in the Tethyan Himalaya, Leo Pargil, northwest India, *Geol. Soc. Am. Bull.*, 118(5–6), 635–650, doi:10.1130/B25872.1.
- Treloar, P. J., P. J. O'Brien, R. R. Parrish, and M. A. Khan (2003), Exhumation of early Tertiary, coesite-bearing eclogites from the Pakistan Himalaya, *J. Geol. Soc.*, 160, 367–376.
- Van der Voo, R., W. Spakman, and H. Bijwaard (1999), Tethyan subducted slabs under India, *Earth Planet. Sci. Lett.*, 171(1), 7–20, doi:10.1016/S0012-821X(99)00131-4.
- Van Hinsbergen, D. J. J., P. C. Lippert, G. Dupont-Nivet, N. McQuarrie, P. V. Doubrovine, W. Spakman, and T. H. Torsvik (2012), Greater India Basin hypothesis and a two-stage Cenozoic collision between India and Asia, *Proc. Natl. Acad. Sci. U.S.A.*, 109(20), 7659–7664, doi:10.1073/pnas.1117262109.
- von Hagke, C., M. Philippon, J.-P. Avouac, and M. Gurnis (2016), Origin and time evolution of subduction polarity reversal from plate kinematics of Southeast Asia, *Geology*, 44(8), 659–662, doi:10.1130/G37821.1.
- Wang, C., X. Li, Z. Liu, Y. Li, L. Jansa, J. Dai, and Y. Wei (2012), Revision of the Cretaceous-Paleogene stratigraphic framework, facies architecture and provenance of the Xigaze forearc basin along the Yarlung Zangbo suture zone, *Gondwana Res.*, 22(2), 415–433, doi:10.1016/j.gr.2011.09.014.
- Warren, C. J., C. Beaumont, and R. A. Jamieson (2008), Modelling tectonic styles and ultra-high pressure (UHP) rock exhumation during the transition from oceanic subduction to continental collision, *Earth Planet. Sci. Lett.*, 267(1–2), 129–145, doi:10.1016/j.epsl.2007.11.025.
- Williams, I. S. (2001), Response of detrital zircon and monazite, and their U-Pb isotopic systems, to regional metamorphism and host-rock partial melting, Cooma Complex, southeastern Australia, *Aust. J. Earth Sci.*, 48(4), 557–580.
- Yin, A., and T. M. Harrison (2000), Geologic evolution of the Himalayan-Tibetan orogen, *Annu. Rev. Earth Planet. Sci.*, 28(1), 211–280, doi:10.1146/annurev.earth.28.1.211.
- Yin, A., T. M. Harrison, M. A. Murphy, M. Grove, S. Nie, F. J. Ryerson, W. X. Feng, and C. Z. Le (1999), Tertiary deformation history of southeastern and southwestern Tibet during the Indo-Asian collision, *Geol. Soc. Am. Bull.*, 111(11), 1644–1664.
- Zhang, H., N. Harris, R. Parrish, S. Kelley, L. Zhang, N. Rogers, T. Argles, and J. King (2004), Causes and consequences of protracted melting of the mid-crust exposed in the North Himalayan antiform, *Earth Planet. Sci. Lett.*, 228(1), 195–212.
- Zhang, R., M. A. Murphy, T. J. Lapen, V. Sanchez, and M. Heizler (2011), Late Eocene crustal thickening followed by Early-Late Oligocene extension along the India-Asia suture zone: Evidence for cyclicity in the Himalayan orogen, *Geosphere*, 7(5), 1249–1268, doi:10.1130/GES00643.S1.
- Zhang, Z., X. Dong, H. Xiang, H. Ding, Z. He, and J. G. Liou (2014), Reworking of the Gangdese magmatic arc, southeastern Tibet: Post-collisional metamorphism and anatexis, *J. Metamorph. Geol.*, 33(1), 1–21, doi:10.1111/jmg.12107.