Along-strike diachroneity in deposition of the Kailas Formation in central southern Tibet: Implications for Indian slab dynamics

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ABSTRACT

The Oligocene–Miocene Kailas Formation is exposed along strike for ~1300 km within the southernmost Lhasa terrane. In this study, we documented the sedimentology, structure, and age of this unit exposed between 87°E and 90°E. Within this region, the Kailas Formation is composed of continental deposits dominated by conglomerate and sandstone, with lesser volumes of siltstone and paleosols. These rocks were deposited nonconformably on Gangdese Batholith and related volcanic rocks along their northern boundary, whereas to the south, the south-dipping Great Counter Thrust places them in contact with Xigaze forearc and mélangé units. We interpret the Kailas Formation to have been deposited in alluvial-fan and fluvial environments with sediment principally derived from the north. Based on sedimentology and structural relationships, we interpret these rocks to have formed in a north-south extensional setting. New zircon U-Pb ages from volcanic tuffs and flows show that Kailas Formation deposition is younger to the east: Deposition occurred between 26 Ma and 24 Ma in western Tibet (81°E), at 25–23 Ma north of Lazi (87.8°E), at 23–22 Ma near Dazhuka (89.8°E), and as late as 18 Ma south-west of Lhasa (92°E). Overall, basin development propagated eastward at a rate of ~300 mm/yr. This pattern and rate of propagation are similar to that of the temporal-spatial distribution of adakitic and ultrapotassic magmatism within the Lhasa terrane to the north, which has been interpreted to represent the result of Indian slab shearing and breakoff, which began in western Tibet around 26 Ma and reached eastern Tibet by ca. 18 Ma.

INTRODUCTION

The rocks of the India-Asia suture zone preserve a record of processes related to the India-Asia collision and the subsequent evolution of southern Tibet. Much previous work has focused on the timing and nature of the India-Asia collision (Besse et al., 1984; Garzanti et al., 1987; Leech et al., 2005; Green et al., 2008; Najman et al., 2010; van Hinsbergen et al., 2015; Wang et al., 2015). Precision dating of the Kailas Formation along the entire India-Asia suture zone is critical to understanding the geodynamic drivers of collisional basin formation and can shed light on the along-strike variations in collision zone evolution. In this study, we present the results of field mapping, sedimentology, and stratigraphy, as well as new U-Pb zircon ages from interbedded tuffs and volcanic rocks for the Kailas Formation preserved between 87°E and 90°E. We show that deposition of the Kailas Formation began in western Tibet around 26 Ma and became progressively younger to the east, arriving at 90°E by 23 Ma.

GEOLOGIC SETTING

The Tibetan Plateau (Fig. 1) formed through the successive accretion of continental fragments to the southern margin of Asia and the closure of their previously intervening oceanic basins (Allègre et al., 1984; Yin and Harrison, 2000). The southernmost of these continental fragments is the Lhasa terrane, which collided with Asia during Early Cretaceous time (Kapp et al., 2007). The appearance of Asian detritus in Tethyan Himalayan (Indian passive margin) strata beginning at ca. 60 Ma has been interpreted to represent the initiation of India-Asia collision after the Neo-Tethyan ocean basin was completely consumed by northward subduction beneath the Lhasa terrane (Ding et al., 2005; DeCelles et al., 2014; Orme et al., 2014; Hu et al., 2015a, 2015b). In contrast, fewer studies have investigated the evolution of this area following initial collision (e.g., Ratschbacher et al., 1994; Wang et al., 2010; DeCelles et al., 2011; Carrapa et al., 2014; G. Li et al., 2015; S. Li et al., 2015), and the geodynamics driving this evolution remain enigmatic. In particular, the geodynamic origin of the thick (>4 km in some localities), continental Kailas Formation, deposited in the center of the largest Cenozoic continent-continent collision zone, is still debated (Aitchison et al., 2002, 2007; DeCelles et al., 2011; S. Li et al., 2015; Wang et al., 2015). However, more significant than the thickness of these deposits is their along-strike continuity: The Kailas Formation is exposed, with some variation in facies, for over 1300 km in Tibet and has been correlated to rocks within the Indus Group several hundred kilometers farther west (Searle et al., 1990). Although initially thought to represent syncontractional deposits related to a flexural basin associated with the late stage of India-Asia collision (Aitchison et al., 2007) or deformation related to the Great Counter Thrust (Yin et al., 1999; Wang et al., 2015), recent investigation in western Tibet (~81°E) indicates that these rocks were deposited in an extensional basin, possibly resulting from Indian slab rollback (DeCelles et al., 2011). Precise dating of the Kailas Formation along the entire India-Asia suture zone is critical to understanding the geodynamic drivers of collisional basin formation and can shed light on the along-strike variations in collision zone evolution. In this study, we present the results of field mapping, sedimentology, and stratigraphy, as well as new U-Pb zircon ages from interbedded tuffs and volcanic rocks for the Kailas Formation preserved between 87°E and 90°E. We show that deposition of the Kailas Formation began in western Tibet around 26 Ma and became progressively younger to the east, arriving at 90°E by 23 Ma.
precollisional Asian margin, continental collision, and subsequent evolution of the southern Tibetan Plateau is preserved in four major lithotectonic zones within southern Tibet, Nepal, and northern India. From north to south, these are the Gangdese magmatic arc, the Xigaze forearc, the India-Asia suture zone, and the Tethyan Himalayan thrust belt. The Gangdese magmatic arc formed initially as an Andean-style arc produced by northward subduction of the Neo-Tethyan slab beneath the Lhasa terrane, and it is dominated by calc-alkaline intrusive and volcanic rocks (e.g., He et al., 2007; Ji et al., 2009; Zhu et al., 2011). The arc was most active between ca. 200 Ma and 40 Ma, with low-volume magmatism continuing as late as 8 Ma (Zhu et al., 2011; Zhang et al., 2014); the highest apparent magmatic flux occurred ca. 52 Ma (Zhu et al., 2011). To the south of the Gangdese arc, the Xigaze forearc represents the remnants of an originally much wider forearc basin that formed on the southern margin of Asia prior to collision (Einsele et al., 1994; Dür et al., 1996; Wang et al., 2012; Orme et al., 2014). Sedimentation in the Xigaze forearc basin began as early as Barremian time and continued until the early Eocene (51 Ma; Einsele et al., 1994; Dür, 1996; Ziegber et al., 2003; Orme et al., 2014; An et al., 2014; Hu et al., 2015a; Huang et al., 2015). South of the forearc basin, the India-Asia suture zone
The Kailas Formation is exposed for ~1300 km along strike (Fig. 1). To the north, the Kailas Formation is with the Triassic Renbu mélange (Cai et al., 2011; Li et al., 2010; the Bainang terrane of Aitchison et al., 2000). Bedding within all Kailas sections studied here dips generally to the south.

At the Xigaze locality, the Kailas Formation is extensively deformed. Folds are slightly north vergent and have wavelengths of 100–500 m (Fig. 5); ~500-m-wavelength isoclinal folds are present in some places. This deformation, in addition to faulting between and within individual members of the Kailas Formation, makes stratigraphic correlation difficult over distances of <1 km.

The Dazhuka section is only slightly deformed. This section dips 40°S and contains an ~100-m-wide footwall syncline below a south-dipping thrust contact with Triassic mélangé rocks (Cai et al., 2011).

**SEDIMENTOLOGY**

We documented the depositional environment of the Kailas Formation through facies analysis of ~3200 m of measured stratigraphic section at three localities (Figs. 6–9; Table 1). In the following, we use the facies classification scheme after Miall (1978). Paleocurrent directions were determined by measurement of clast imbrications (~10 individual measurements per site) and analyses of trough cross-bedded sandstones (method I in DeCelles et al., 1983).

The Kailas Formation in western Tibet has been divided into four major lithologic divisions: a lower conglomeratic interval, a fluvial sandstone interval, and an upper conglomeratic red-bed interval. The structural setting and section localities

**STRUCTURAL SETTING AND SECTION LOCALITIES**

For this study, we examined the Kailas Formation in three separate localities (Fig. 2). The westernmost of these, referred to as the “Lazi locality,” is located ~30 km northeast of the town of Lazi (Fig. 3); the central locality, referred as the “Xigaze locality,” is exposed ~20 km northwest of the city of Xigaze (Fig. 4); and the easternmost section, the “Dazhuka locality,” is exposed ~15 km east of the town of Dazhuka in the Yarlung Zangbo gorge (Fig. 2). The structural boundaries of the Kailas Formation are all generally similar. Along its northern boundary, the Kailas Formation was deposited in buttress unconformity on Gangdese arc rocks. To the south, the Kailas Formation is disrupted by folds and faults attributed to the southward-dipping Great Counter Thrust system (Fig. 2), which in some places juxtaposes Xigaze forearc deposits against the Kailas Formation. At the Dazhuka locality, the southern thrust contact of the Kailas Formation is with the Triassic Renbu mélangé (Cai et al., 2011; Li et al., 2010; the Bainang terrane of Aitchison et al., 2000). Bedding within all Kailas sections studied here dips generally to the south.

The deformation experienced by the Kailas Formation varies considerably along strike. In the Lazi section, most of the section is not folded, although a few, ~30-m-wavelength recumbent folds are present. In the upper (southern) portion of the Lazi section, an ~100-m-thick, vertical to south-dipping ductile shear zone cuts through the Kailas Formation. Granitic cobbles deformed as sigma and delta clasts within this zone indicate top-to-the-north sense of shear (Fig. 3).

The India-Asia suture zone and the Xigaze forearc basin are cut and deformed by a series of north-vergent thrust faults collectively referred to as the Great Counter Thrust system (Heim and Gansser, 1939; Ratschbacher et al., 1994; Yin et al., 1994, 1999; Murphy et al., 2010; Sanchez et al., 2010a, 2010b). The Great Counter Thrust is the northernmost fault system in the Tethyan Himalayan thrust belt; movement along this fault began as early as ca. 25 Ma and continued until ca. 16 Ma, based on structural relationships and thermochronometric ages (Ratschbacher et al., 1994; Harrison et al., 2000; Yin, 2006; Murphy et al., 2010; Sanchez et al., 2010a). In various localities along strike, the Great Counter Thrust places Tethyan Himalayan rocks over suture zone rocks, Xigaze forearc rocks above the Kailas Formation, or ophiolitic and Tethyan rocks over other Cenozoic conglomerates within the suture zone such as the Liuqu Conglomerate. Displacement estimates for the Great Counter Thrust are >38 km in western Tibet (Murphy and Yin, 2003) and between >12 km and 60 km in eastern Tibet (Yin, 2006).

The Kailas Formation is exposed for ~1300 km along strike (Fig. 1). To the west, it has been correlated with lithologically similar rocks of the Indus Group in the northwestern Himalaya (Searle et al., 1990; Sinclair and Jaffey, 2001). These rocks have been referred to by numerous local names along strike, such as the Kailas conglomerate (Heim and Gansser, 1939; Gansser, 1964) and the Kailas Formation (Cheng and Xu, 1986; DeCelles et al., 2011) in western Tibet; and the Guwu (Wang et al., 2013), Dazhuka (Aitchison et al., 2009), and Loubusa Formations (Yin et al., 1999) in the central segment of the suture zone. Aitchison et al. (2002) grouped all of these units into the Gangrinboche Conglomerate, whereas S. Li et al. (2015) referred to this group of rocks as the Gangdese Conglomerate. In this study, we use the term “Kailas Formation” (Cheng and Xu, 1986; DeCelles et al., 2011) to refer to the entire east-west extent of these lithologically and structurally similar sedimentary rocks.

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The Kailas Formation in western Tibet has been divided into four major lithologic divisions: a lower conglomeratic interval, a fluvial sandstone interval, and an upper conglomeratic red-bed interval. (DeCelles et al., 2011). This general stratigraphy is not maintained in the field areas of this study. This along-strike variation could have arisen because of poor preservation in the current study area or could be due to differing basin and depositional conditions along strike. Here, we examine the sedimentology of each major locality individually, from west to east.
Lazi Locality

At the Lazi locality (Figs. 2, 6, and 7), the Kailas Formation is ~1000 m thick. This section is divided into three different lithologic members: a basal conglomerate, a middle sandstone member, and an upper conglomerate. The basal conglomerate (section 1KS) was deposited nonconformably on Gangdese arc granite and is ~690 m thick. The lower ~400 m of this section is characterized by massive, matrix-supported cobble to boulder conglomerates (Gmm) and massive, clast-supported pebble to cobble conglomerate (Gcm). Above the 400 m level, these facies transition into horizontally stratified, clast-supported (Gch) and imbricated (Gci) conglomerates (Fig. 10B). In the upper portion of this member, horizontally stratified, clast-supported cobble conglomerates (Gch) are interbedded with massive and horizontally stratified sandstones (Sm and Sh) and fine-grained intervals; fine-grained intervals consist primarily of horizontally laminated siltstone (Fsh) and paleosols (Fp). Conglomerate beds in this member range from ~1 to ~12 m thick, with an average thickness of ~8 m. Clast-supported conglomerates typically show erosion and channelization at their bases. Paleocurrent directions within the lower member are dominantly northward (Fig. 6).

The middle member at this location (1KS and 2KS) is >120 m thick and is dominated by thinly bedded (<10 cm), laterally extensive, horizontally stratified sandstone (Sh) beds separated by horizontally laminated red siltstone (Fsl). Sandstone beds generally show fining-upward trends. Trough cross-bedded (St) and horizontally stratified (Sh) sandstone beds between 1 m and 5 m thick are also occasionally present. Sparse clast-supported, horizontally stratified conglomerate beds are present, and one thick (~15 m) trough cross-stratified sandstone (St) showing numerous lateral accretion elements was documented (Fig. 10A). Paleocurrent measurements from this sandstone unit are southward and are perpendicular to the dip of the accretion elements.

The upper conglomeratic member is ~210 m thick. It consists of 1–6-m-thick, clast-supported, horizontally stratified pebble conglomerates (Gch) interbedded with red paleosols (Fp) and red horizontally laminated siltstones (Fig. 10C). Minor volumes of trough cross-stratified (St) and horizontally stratified (Sh) sandstone are also present. The bases of most conglomeratic intervals are scoured and channelized. Paleocurrent indicators from this section show eastward sediment transport (Figs. 6 and 7). One tuffaceous bed containing volcanic ash, biotite grains, and reworked sand is present in the upper portion of this member. Dating of this layer provides the best constraint on the age of this section (see later herein).

The dominance of the Gmm facies at the base of the lower member suggests deposition by sediment-gravity flows in the proximal portion of an alluvial fan (Shultz, 1984; Blair and McPherson, 1994; Singh et al., 2001). The facies association within the upper portion of this member (Gch, Gcm, Sh, St, Fp) suggests deposition by fluvial processes in a more distal alluvial-fan setting.
Figure 3. Geologic map of the Lazi locality. 1KS–4KS refer to measured sections.
The facies within in the middle member of the Kailas Formation at this location suggest deposition in a fluvial setting. Thick, trough cross-stratified sandstone (St) bodies represent deposition by strong, unidirectional currents in major channels (Ashley, 1990; Ashworth et al., 2011); lateral accretion elements in one of these bodies that dip perpendicular to measured paleocurrent indicators suggest that channels in this interval were of moderate to high sinuosity (Miall, 1985; Miall and Turner-Peterson, 1989). Fine-grained intervals within this member likely represent floodplain and overbank deposits, whereas thin, tabular sandstone bodies are interpreted as crevasse splay deposits (Miall, 1985; Smith et al., 1989; Bristow et al., 1999).

We interpret the coarse, channelized conglomerate beds (Gch) in the upper member to represent fluvial channels on a stream-dominated alluvial fan (Rust, 1977; Allen, 1981; Ori, 1982; Nemic and Steel, 1988; Ridgway and DeCelles, 1993). Horizontally stratified sandstone (Sh) intervals within this member likely represent deposition in upper-flow-regime conditions during floods (Cant and Walker, 1976; Allen, 1981). Paleosols most likely represent weathering in the interfluve regions of the fan, whereas laminated siltstone (Fsi) likely represents suspension settling in marshy overbank environments (Allen, 1981; Evans, 1991).

**Xigaze Locality**

The Kailas Formation at the Xigaze locality is structurally disrupted by folds and faults, making correlation of members and interpretation of stratigraphic position difficult (Fig. 5; Wang et al., 2013). In this study, we follow the stratigraphic divisions of Wang et al. (2013), who divided the Kailas Formation into two formations: the Quiwu Formation (lower) and the Dazhuka Formation (upper). The Quiwu Formation is ~400 m thick and is made up of sandstone, coal, and carbonaceous shale (Wang et al., 2013). Based on sedimentology and paleocurrents, Wang et al. (2013) interpreted this to represent a lacustrine depositional environment that drained southward away from rocks of the Gangdese Batholith.
Because the Qiuwu Formation is poorly exposed over a very limited area, we focus here on the Dazhuka Formation. The Dazhuka Formation is divided into the Jiangqingze (lower), Deri (middle), and Tunqiong Members (upper). The Jiangqingze Member (Fig 8) is 685 m thick and is exposed in a series of east-plunging folds (Fig. 5). It is dominated by thick (~10 m), horizontally stratified sandstone (Sh) bodies separated by red, bioturbated paleosols (Fp) and red laminated siltstones (Fsl). Many of these sandstone bodies have scoured bases. Trough cross-stratified sandstones (St) are also present, although they make up only a small volume of this member. Thinner (<1 m thick), horizontally stratified, upward-fining sandstone beds are commonly interbedded with fine-grained intervals.

The Deri Member is up to 1800 m thick (Wang et al., 2013), although numerous thrust faults within this section make this a maximum estimate. We documented part of the Deri Member by measuring 440 m of unfaulted strata along the north limb of an east-plunging, ~500-m-wavelength anticline. This section is dominated by thick (10–20 m), clast-supported, horizontally stratified (Gch) and imbricated (Gchi) pebble-cobble conglomerates (Fig. 10E). Clasts are well rounded and well sorted. These beds are separated by trough cross-stratified (St) and horizontally stratified (Sh) sandstones and sparse paleosols (Fp).

The entire Tunqiong Member where it was measured for this study is 185 m thick and exposed in an east-plunging, ~400-m-wide syncline structurally beneath the Great Counter Thrust. Wang et al. (2013) reported that this member is as thick as 750 m to the east. This member is dominated by thinly bedded rippled sandstone (Sr) interbedded with red paleosols (Fp) and sparse laminated siltstone (Fsl). The thinnest of these sandstone beds are often laterally discontinuous, whereas thicker intervals are laterally extensive over several hundred meters. Paleosols are bioturbated, rooted, and contain sparse carbonate nodules; 5–10-m-thick rippled sandstone bodies are present in the upper portion of this section, and two ~2-m-thick clast-supported massive pebble conglomerates (Gch) are present in the upper portion of this member.

We interpret the lithofacies assemblage of the Jiangqingze Member as representing deposition in a fluvial system. Thick (5–10 m), horizontally stratified (Sh) and trough cross-stratified (St) sandstone bodies with erosional bases are interpreted to have been deposited by strong, unidirectional currents within fluvial channels (Cant and Walker, 1978; Bridge and Lunt, 2006; Ashworth et al., 2011). Paleosols (Fp), massive siltstone (Fsm), and laminated siltstone (Fsl) are interpreted as overbank deposits. Thin (<1 m), fining-upward sandstone beds are interpreted to have been deposited within crevasse splays during splay abandonment (Miall, 1985; Smith et al., 1989; Bristow et al., 1999). This overall interpretation is consistent with that of Wang et al. (2013).

Also consistent with the conclusions of Wang et al. (2013), we interpret the lithofacies preserved in the Deri Member as representing a high-energy fluvial...
Figure 6. Measured section from Lazi locality. Stratigraphic height is in meters. See Figures 2 and 3 for location. See Table 1 for lithofacies codes.
system. Clast-supported, horizontally stratified (Gch) and imbricated conglomerates (Gchi) likely represent deposition by gravel bars within main channels (Rust, 1977; Allen, 1981; Wooldridge and Hickin, 2005). Trough cross-stratified sandstones (St) are interpreted as deposits of subaqueous dune forms in sandy channels (Rust, 1977; Ashley, 1990; Bridge and Lunt, 2006; Ashworth et al., 2011). Sparse fine-grained material is interpreted as overbank deposits.

The lithofacies assemblage of the Tunqiong Member is interpreted to represent distal overbank deposits of a fluvial system. Tabular, laterally continuous rippled sandstone beds are interpreted as crevasse splay deposits formed during avulsion events (Miall, 1985; Smith et al., 1989; Bristow et al., 1999). Rippled, lenticular sandstone bodies are interpreted as the toes of crevasse splays and levees (Allen, 1964; Bristow et al., 1999). Abundant red paleosols are interpreted to have developed on exposed overbank areas between major floods (Allen, 1964; Miall, 1985). This assemblage of geomorphic elements (paleosols, crevasse splays, levees) is typical of fluvial floodplain environments, rather than alluvial fans (as suggested by Wang et al., 2013).

**Dazhuka Locality**

The Kailas Formation exposed at the Dazhuka locality was previously referred to locally as the Dazhuqu conglomerate (Aitchison et al., 2007). This section includes ~740 m of strata, which we divide into informal upper and lower members (Fig. 9). The lower member rests nonconformably on Gangdese granite, although the contact is covered by Quaternary colluvium.

The lower member at this location is composed almost entirely of massive, disorganized, and poorly sorted, clast-supported boulder conglomerate (Gcm; Fig. 10F). Beds range in thickness between 1 m and 25 m, and the largest clast sizes are up to 3 m in diameter. The matrix is primarily poorly sorted sandstone. Clasts range from subangular to subrounded, with more-resistant lithologies such as volcanic rocks making up the bulk of the subangular clasts, and less-resistant lithologies such as limestone and marble forming the more rounded clasts. Some beds are inversely graded. Several porphyritic trachyandesite flows containing abundant subangular to rounded clasts of varying lithologies (Gma) are preserved in this section (Fig. 10G). Very little fine-grained material is preserved in this section; however, several weakly developed paleosols (Fp) were observed.

The upper member is finer grained and dominated by horizontally stratified sandstone (Sh) in beds ranging in thickness from 10 cm to 10 m; typical bed thickness is ~1–2 m. Many of these sandstones are interbedded with ~10-cm-thick intervals of massive, clast-supported granule to pebble conglomerate. Massive, clast-supported pebble to cobble conglomerate (Gcm) is also preserved in occasional 1–10-m-thick beds. This member lacks siltstone and paleosol intervals.

We interpret the abundance of massive, clast-supported (Gcm) intervals within the lower member as representing deposition by hyperconcentrated flood flows (e.g., Smith, 1986) or high-density traction carpets (e.g., Todd, 1989) in a proximal alluvial fan. Sparse massive or coarsening-upward,
Figure 8. Measured section from Xigaze locality. Stratigraphic height is in meters. See Figures 2 and 4 for location, Table 1 for lithofacies codes, and Figure 6 caption for legend.
Figure 9. Measured section from Dazhuka locality. Stratigraphic height is in meters. See Figure 2 for location, Table 1 for lithofacies codes, and Figure 6 caption for legend.

matrix-supported conglomerates (Gmm) are interpreted as typical high-viscosity debris-flow deposits (Pierson, 1980; Shultz, 1984). Trachyandesite flows (Gma) are interpreted to represent deposits of pyroclastic density currents from Gangdese volcanic centers that incorporated accidental clasts while traveling across the alluvial landscape (e.g., Bryan et al., 1998). The presence of these deposits, the coarseness of this member, and the dominance of volcanic clasts all indicate that this locality was proximal to the active Gangdese arc at the time of deposition.

The upper member is interpreted to represent deposition in the medial to distal portions of an alluvial-fan system. Horizontally stratified sandstone (Sh) is interpreted to represent upper-flow-regime conditions during sheetfloods (Bull, 1972; Blair and McPherson, 1994; Blair, 2000), and the clast-supported conglomerates (Gcm) are interpreted to represent basal sheetflood deposits (Blair and McPherson, 1994; Blair, 2000) or hyperconcentrated flow deposits (Smith, 1986) because of their poorly organized structure.

CHRONOSTRATIGRAPHIC CONTROL

U-Pb geochronology provides chronostratigraphic control for the Kailas Formation. Samples were collected from one tuff, a trachyandesite flow, and seven medium- to coarse-grained sandstone beds. Zircon crystals were extracted following standard methods of crushing, panning, magnetic separation with a Frantz machine, and heavy liquids. Grains were then mounted in epoxy pucks and analyzed at the University of Arizona LaserChron Center. All samples from section 1KS were analyzed on an Element2 single-collector mass spectrometer, whereas all other samples were analyzed using a Nu laser-ablation–multicollector–inductively coupled plasma–mass spectrometer following the methods of Gehrels et al. (2006, 2008) and Gehrels and Pecha (2014).

At the Lazi locality, a detritally contaminated tuff from the upper portion of section 3KS (3KS-105) provides tight constraint on the age of the Kailas Formation (Fig. 11). Although this sample contained significant numbers of older detrital grains, the youngest population of grains at 22.8 ± 0.3 Ma (n = 43) provides an age that is likely very close to the eruptive age of the tuffaceous material and the depositional age of this sample. Additional samples from the Lazi section (1KS-408, 1KS-754, 2KS-188) each contain one young grain between 21 Ma and 23 Ma; the youngest statistically significant population is ca. 50 Ma in each of these samples and does not provide a useful maximum depositional age. There are no unconformities or major faults within the Lazi section, which rules out the possibility of a ca. 50 Ma basal section and a much younger upper section. These ages are comparable to the results of S. Li et al. (2015), whose U-Pb detrital zircon data yielded maximum depositional ages of 21 Ma (basal Kailas Formation) and 15 Ma (upper Kailas Formation) from a section 20 km to the west.

Samples from the Xigaze section (1XK-10, 1XK-313, 2XK-47) contained no syndepositional age grains. Sample 1XK-10 contained two ca. 32 Ma grains, with the youngest statistically significant population at 50 Ma (Fig. 11). Samples 1XK-313 and 2XK-47 contained single youngest grains at 32 Ma and 29 Ma, respectively; again, both of these samples had the youngest statistically
significant populations at 50 Ma. These results are consistent with the analyses of Wang et al. (2013), who reported a single 31 Ma grain at the base of this section as well as palynology results suggesting that the Qiuwu Formation (stratigraphically below 1XK) was deposited during late Oligocene time (Li, 2004).

In the lower portion of the Dazhuka locality, zircons from a trachyandesite flow yielded a U-Pb age of 22.9 ± 0.3 Ma ($n_2 = 64$; 1DK-246; Fig. 1). This age is consistent with the 40Ar/39Ar (biotite and plagioclase) ages between 22.3 ± 0.7 Ma and 19.5 ± 0.2 Ma reported by Aitchison et al. (2009) from a felsic tuff in this section.

Although ages for the Kailas Formation in this study are very similar, it is important to note that the age of the lower portion of section 1DK is nearly the same age as the upper portion of section 3KS, exposed to the west. This indicates that the Kailas Formation may be slightly younger in the eastern area of this study (see later herein). However, it must be acknowledged that the sections considered here are all partial sections, so it remains possible that they represent different parts of the Kailas Formation.

## PROVENANCE

### Conglomerate Clast Composition

Clast composition of the Kailas Formation was determined primarily by clast counts at 15 sites covering the complete geographic and stratigraphic extent of this study. At each station, at least 100 clasts were identified. At the Lazi locality (sections 1–4KS; Fig. 12), clasts at the base of the lower member are dominated by granite, with 15% volcanic clasts. The middle portion of the lower member contains nearly equal portions of granite and volcanic clasts, with sparse sedimentary clasts; in the upper portion of the lower member, clasts are almost entirely volcanic.

The Kailas Formation north of Xigaze (sections 1–2XK, 1YZ; Fig. 8) is far more compositionally diverse than the other sections examined in this study and includes abundant chert, sandstone, and volcanic clasts, with minor amounts of granite and siltstone. There are no significant up-section changes in clast type at this location.

At the Dazhuka locality (section 1DK; Fig. 9), the lower member is dominated by granite and volcanic clasts; chert, limestone, basalt, and sandstone are present in minor volumes. Chert and lithic sandstone are found in secondary amounts, whereas quartzite, white sandstone, serpentinized material, and granite are found in trace amounts.

### Modal Sandstone Petrography

Modal framework-grain compositions of six representative sandstone samples were determined by point-counting 450 grains per thin section following a modified Gazi-Dickinson method (Ingersoll et al., 1984) to corroborate the clast compositional data. Standard petrographic slides were stained for...
Figure 10. Photographs of Kailas Formation outcrops. (A) Middle member at section 2KS, Lazi locality showing lateral accretion elements. (B) Weakly imbricated clast-supported cobble conglomerate from the lower member of section 1KS, Lazi locality. (C) Upper member at 3KS, Lazi locality. (D) Ductilely deformed granitic clasts within the mylonitic shear zone cutting the Kailas Formation; Lazi locality. (E) Imbricated clast-supported cobble conglomerate, Deri Member, Xigaze locality. Jake staff is 1.5 m. (F) Lower member, section 1DK, Dazhuka locality. (G) Trachyandesite within a welded conglomerate, Dazhuka locality.
Figure 11. Probability density plots, histograms, and maximum depositional ages of Kailas Formation detrital zircons (see Figs. 2–4 for locations). Histogram bin width is 5 Ma for 0–200 Ma plots and 20 Ma for 200–2000 Ma plots. Number at top left of each plot indicates the maximum vertical extent of the histogram y-axis. Maximum depositional ages were calculated using Unmix Ages (Ludwig, 2012) and by weighted average. Uncertainty reported is total 2σ uncertainty. Analyses in blue were excluded in the weighted average. Sources for Lhasa terrane compilation: Guillaume et al. (1997); Chung et al. (2003); Mo et al. (2003); Kapp et al. (2005, 2007); Guynn et al. (2006); He et al. (2007); Ji et al. (2009); Volkmer et al. (2007); Wen et al. (2008); Xu et al. (2010); Zhu et al. (2009, 2010, 2011); and DeCelles et al. (2011).
Figure 12. (A) Clast count histograms: 1—red chert, 2—green chert, 3—black chert, 4—quartzite, 5—green lithic sandstone, 6—brown sandstone, 7—white sandstone, 8—limestone, 9—volcanic, 10—basalt, 11—granite; s.s.—sandstone. (B) Results of sandstone points. Fields are after Dickinson (1985). Qm—monocrystalline quartz; F—feldspar; Lt—total lithic grains; Qt—total quartzose grains; Lm—metamorphic lithic grains; Lv—volcanic lithic grains; Ls—sedimentary lithic grains.
Ca-plagioclase and K-feldspar to aid in their identification. Specific composition percentages are presented in the Supplemental File.

Quartzose grains include monocrystalline (Qm), polycrystalline (Qp), and tectonized polycrystalline (Qtp) varieties and chert (Qch). Feldspars are primarily albite with trace amounts of K-feldspar. Lithic volcanic grains include felsic, vitric, and latite/kratonic (Lv, Lvv, Lvl) types and rare mafic grains containing pyroxene and altered mafic minerals. Most volcanic grains are heavily sericitized. Sedimentary lithic grains include phylite (Lph) and siltstone (Lsilt). Accessory minerals include muscovite, pyroxene, and serpentine. Cement is most commonly calcium carbonate with abundant sericite alteration. Plotted in ternary diagrams (Fig. 12), Kailas Formation sandstones lie between the transitional arc and dissected field of Dickinson (1985).

Detrital Zircon Ages

Detrital zircon age spectra differ significantly between localities (Fig. 11). At the Lazi locality, nearly all grains are younger than 100 Ma, with only a single grain older than 200 Ma. At the Dazhuka locality, all grains except for one are younger than 100 Ma. Samples from both of these locations contain large peaks at 50 Ma and minor peaks at 90 Ma. Two samples contain large, near-depositional-age peaks at 23 Ma from tuffs or volcanic flows as mentioned already. In contrast, samples from the Xigaze locality contain large peaks around 50 Ma and 90 Ma, minor peaks at 190 Ma and 360 Ma, and scattered single grains between 500 Ma and 3200 Ma.

In western Tibet (~82°E), detrital zircon spectra show peaks at 23 Ma, 50 Ma, and 90 Ma, with grains older than 100 Ma making up as much as 30% of each sample (DeCelles et al., 2011; S. Li et al., 2015). In this study, samples from the Lazi and Dazhuka localities contained <4% scattered, single grains older than 100 Ma. In samples from the Xigaze locality, these grains make up ~15% of total grains. Farther east, samples from the Kailas Formation (Luobusha conglomerate) yielded a few grains at 23 Ma and high-amplitude peaks at 50 Ma and 90 Ma (Li et al., 2015). Grains older than 100 Ma make up between 15% and 30% of these samples.

Kailas Formation U-Pb detrital zircon age spectra share major similarities to Gangdese pluton ages (Fig. 11). The southern Gangdese arc experienced four primary magmatic stages around 13–33 Ma, 45–55 Ma (the most voluminous), 80–100 Ma, and 170–190 Ma (Ji et al., 2009, 2014; Zhu et al., 2011). The youngest documented intrusive rocks in the Lhasa terrane are 8–9 Ma (Kapp et al., 2005; Sundell et al., 2013).

Provenance Interpretation

Provenance data from the Lazi locality are consistent with the sedimentology in suggesting deposition proximal to the sediment source. Abundant granite clasts at the base of the section were likely derived from nearby Gangdese granites. Higher in the section, clasts are entirely volcanic, suggesting either a change in catchment to a more volcanic-rich source area or that granites in the catchment(s) of this depositional system were buried by volcanic rocks during Kailas deposition. Detrital zircon U-Pb data are consistent with this provenance interpretation; large populations at 50 Ma reflect erosion and recycling of material from Gangdese granite, and the presence of ca. 23 Ma grains (including the dated stuff) suggests input via air fall from active Gangdese volcanic centers to the north. Generally north-directed paleocurrents in the lower member of the Kailas Formation at this site contrast with the dominantly southward indicators found elsewhere along strike (DeCelles et al., 2011; Wang et al., 2013).

We interpret northward flow in this member to indicate that this portion of the Kailas Formation was deposited in a small, north-facing catchment that fed a larger, south-directed sediment transport system. Although no granitic rocks are currently exposed south of this locality, a localized granitic upland may have existed south of the Lazi locality during initial Kailas basin subsidence; in this scenario, that upland would have been subsequently eroded or structurally buried. Alternatively, it is possible that the measured clast imbrications could represent apparent imbrications formed as armor on gravel bar flanks, rendering them meaningless as paleocurrent indicators. South- and east-directed paleocurrent indicators in the middle and upper members at this location, as well as more distal fluvial and alluvial facies, indicate that deposition at this site was integrated into a larger southward or perhaps axial drainage system. However, despite this possibility, the source for Kailas sediment at this location remained monolithologic.

Clast count data from the Xigaze section show much greater compositional variety within the Kailas Formation, and detrital zircon age spectra show a much larger range of U-Pb ages. The abundance of lithologies exposed primarily south of the India-Asia suture zone, such as chert, quartzite, and white sandstone, suggests that sediment was being derived from the south. However, the presence of volcanic and granitic clasts suggests a northern, Gangdese source as well. A similar pattern is observed in the detrital zircon data, where minor age peaks at 29 Ma and 34 Ma, as well as major peaks around 50 Ma and 90 Ma, suggest a Gangdese source; minor peaks at 190 and 360 Ma and scattered older ages may suggest a southern source in the accretionary melange or Tethyan Himalaya. However, these samples contain very few 130 Ma grains, which are abundant in melange rocks, and we interpret this low abundance of 130 Ma zircon grains to be the result of dilution by more zircon-rich Gangdese sources to the north. We suggest that this locality was integrated into the larger Kailas Formation depositional system, which would have included axial transport and sediment input from both sides of the India-Asia suture zone (Wang et al., 2013). The predominance of fluvial facies at this location is consistent with this interpretation, as are south-southeast (this study) and west-northwest (Wang et al., 2013) paleocurrent indicators. It is worth noting, however, that deformation in this location is strong, making it impossible to rule out vertical-axis rotation of measured beds, and paleocurrent indicators from this section should be interpreted cautiously.

Abundant granite and volcanic clasts in the lower member of the Dazhuka locality show similar composition to those in the Lazi locality. The limited range of clast compositions, detrital zircon age peaks at 23 Ma and 50 Ma, and prox-
mal alluvial-fan facies are interpreted to represent deposition in a small catchment near the sediment source. The upper member of this section however, shows clast compositions that are very similar to those found at the Xigaze location. We interpret this as the integration of a spatially confined alluvial-fan system (lower member) into a larger alluvial/fluvial system with a much larger catchment that supplied some sediment (chert, lithic sandstone, and quartzite) to the studied location. Distal alluvial/fluvial facies in the upper member are consistent with this interpretation.

**DISCUSSION**

**Mechanism of Subsidence and Basin Formation**

The basin type and mechanism of subsidence that accommodated Kailas Formation deposition are debated. Yin et al. (1999), Aitchison et al. (2002, 2009), and Davis et al. (2004) interpreted the unit to represent deposition in a contractional setting associated with uplift of rocks in the Great Counter Thrust hanging wall. Wang et al. (2015) interpreted the Kailas Formation as having been deposited in a flexural foreland formed by loading by the Great Counter Thrust. DeCelles et al. (2011) and Wang et al. (2013) interpreted the Kailas basin to have formed in an extensional setting associated with rollback of the subducted Indian continental slab. Determining whether the Kailas basin was extensional or contractual is a key factor in a correct interpretation of the tectonic significance of the basin.

The Kailas Formation exposures examined in this study are not as stratigraphically complete, regionally extensive, or structurally intact as those in western Tibet (~81°E), from which the extensional basin interpretation was originally drawn. However, several important structural and stratigraphic features within the rocks examined for this study point to a similar extensional origin for this portion of the Kailas Formation.

Along the entirety of its ~1300 km strike, the northern boundary of the Kailas Formation is nonconformable on Gangdese granite. The only deformation associated with this contact is southward tilting. Paleocurrent indicators, clast counts, and sandstone petrography indicate that the majority of the Kailas Formation was derived from the Gangdese magmatic complex (including both granitic and volcanic rocks) located to the north, although there is some local variation (e.g., the Lazi locality). This structural and stratigraphic geometry is not typical of syncontractional conglomerates, which are typified by clast types different than the depositional substrate and which often contain growth strata that fan away from the thrust belt (Anadón et al., 1986; Vergés et al., 2002). Additionally, syncontractional deposits (wedge-top deposits) are often typified by strata that coarsen upward as the sediment source. The Kailas Formation is arranged in a "very coarse-grained → fine-grained → coarse-grained" stratigraphic arrangement, i.e., more typical of extensional basins (Schlische, 1992; DeCelles et al., 2011). Although the Xigaze locality does not exhibit this stratigraphic arrangement, the facies progression at this location is still atypical of convergent deposits and can be explained by local variation along strike or differing preservation along strike. It is also likely that the Xigaze section is equivalent only to the upper part of the Kailas Formation, based on its composition.

Large-scale (>1 km) growth strata within the Kailas Formation were documented by Wang et al. (2015). Wang et al. (2015) interpreted these as a result of north-vergent contractional structures; however, the southwestern fanning stratigraphic geometry is not consistent with structural growth to the south of the Kailas basin as envisioned by Wang et al. (2015). Instead, these growth strata are better interpreted as the result of southward-increasing accommodation space in an asymmetric half graben with the main fault dipping northward along the south flank of the basin (Fig. 13). Although minor extensional features can be found in overall convergent settings, kilometer-scale growth strata such as those pictured by Wang et al. (2015) and herein (Fig. 13) indicate an extensional origin (Leeder and Gawthorpe, 1987; Schlische and Olsen, 1990; Schlische, 1992; Coogan and DeCelles, 1996; Shaw et al., 1997), and the geometries observed are atypical of growth strata formed in contractional settings (for examples of contractional growth strata, see Anadón et al., 1986; DeCelles et al., 1987, 1991; Lawton et al., 1998; Vergés et al., 2002).

One perplexing aspect of an extensional origin for the Kailas Formation is the lack of preserved normal faults. Although some authors have interpreted this to preclude an extensional origin for the basin (Wang et al., 2015), we argue that the fault or faults bounding the basin to the south have been tectonically buried by the Great Counter Thrust hanging wall, which was emplaced after Kailas Formation deposition (Fig. 13). In the current study area, the north-south extent of Kailas Formation exposure is no more than 2 km, and only the northernmost portion of the basin is exposed. As such, the normal fault(s) that controlled Kailas basin subsidence are not expected to be preserved at the surface. In western Tibet, the preserved Kailas Formation is ~10 km wide. Based on proximal facies near the southern outcrop boundary, such as boulder conglomerates and Gilbert deltas, the southern basin margin is interpreted to have been within several kilometers of the southern exposure boundary (DeCelles et al., 2011). However, as in central Tibet, that boundary is buried by the Great Counter Thrust hanging wall, and the basin-bounding normal fault(s) is(are) not directly observed.

In addition to stratigraphic architecture and growth strata, there are several other features of the Kailas Formation that preclude deposition within a contractual or foredeep setting as suggested by Wang et al. (2015).

Wang et al. (2015) argued that the Gangdese belt, which sits ~700 m higher than the Tibetan Plateau to the north, is a flexural forebulge. In this model, the Kailas Formation represents the foredeep to this system. However, the topographic amplitude of a flexural forebulge is typically an order of magnitude less than the depth of the foredeep basin (Beaumont, 1981; DeCelles and Giles, 1996; Allen and Allen, 2006). In order for the proposed Gangdese "flexural forebulge" to have an amplitude of ~700 m, the Kailas basin would have been up to 11 km deep and at least 80 km wide (Wang et al., 2015; Fig. 4), yet the thickest accumulation of Kailas Formation strata is only ~4 km (DeCelles et al., 2011;
Wang et al., 2013). Both margins of the Kailas basin are well documented by the presence of very coarse boulder conglomerates that could not have been transported more than a few kilometers (DeCelles et al., 2011). Where these margins are documented, the basin could not have been more than ~15 km in north-south width, i.e., far less than the >80-km-wide Kailas basin required by the model of Wang et al. (2015).

Wang et al. (2015) interpreted 23.4 Ma to 16.4 Ma apatite fission-track ages from the Gangdese arc to indicate a pulse of rapid exhumation related to forebulge uplift. Assuming a geothermal gradient of 30 °C/km (Carrapa et al., 2014), these ages require at least several kilometers of exhumation to have taken place in the Gangdese arc as a result of forebulge uplift. Although this magnitude of erosion is hypothetically possible for a large forebulge, erosion associated with the development and migration of forebulges is typically very slow, ranging from 0.01 to 0.1 mm/yr (Crampton and Allen, 1995; Sinclair, 1997). These rates are far too slow to result in several kilometers of exhumation over the ~5 m.y. duration of proposed flexural activity (Wang et al., 2015).

**Burial History of the Kailas Formation**

Numerous lines of evidence support the conclusion that the processes driving subsidence and sedimentation for the Kailas Formation were similar along strike; however, there is good evidence that these rocks experienced very different burial and exhumation histories subsequent to deposition. First, the physical deformation state of these rocks changes significantly along

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**Figure 13.** Photographs from Wang et al. (2015), SI1–8a, showing extensional growth strata within the Kailas conglomerate (cngt) taken (A) 15 km and (B) 5 km west of Mt. Kailas in western Tibet (81°E). (C) Schematic depiction of our interpretation of the structure of the Kailas basin, matching growth structures shown in A and B. (D–F) Schematic postdepositional evolution of the Kailas basin. (D) Schematic cross section of the Kailas basin near the end of sedimentation. (E) Schematic cross section showing future locations of Great Counter Thrust (GCT) in (1) this study area and (2) western Tibet (~81°E). Blue box shows currently exposed portion of the basin in this study area; red box shows currently exposed basin in western Tibet. (F) Schematic cross section of modern Kailas basin structure.
strike: In the Mt. Kailas region, the Kailas Formation is only mildly deformed by brittle faults along its southern margin (DeCelles et al., 2011); the same is true of the Kailas Formation for as much as 500 km east of Mt. Kailas and for rocks at the Dazhuka locality. However, Kailas Formation rocks in the center of the current study area depart from this trend. North of Xigaze, the Kailas Formation is folded into tight, occasionally isoclinal, folds; at the Lazi locality, the southern edge of the Kailas Formation is bounded by a ductile shear zone (Figs. 3 and 10).

Similar along-strike heterogeneities are observed in the temperature histories of Kailas Formation rocks. In the Mt. Kailas region, zircon (U-Th)/He ages are a mix of reset and unreset, indicating that burial temperatures were between 120 °C and 230 °C (Carrapa et al., 2014); zircon (U-Th)/He ages from the Kailas Formation exposed near Sangsang (“Geydo section” in Carrapa et al., 2014) are unreset, indicating that burial temperatures there did not exceed 200–230 °C. However, in exposures north of Saga (east of the Lopukangri Range), zircon (U-Th)/He ages are reset, indicating that burial temperatures exceeded 200–230 °C. Although no thermochronometric data exist for the current study area, rough temperature constraints can be supplied by the ductile behavior of granitic clasts within the mylonitic shear zone that truncates the southern Kailas exposure at the Lazi locality. In typical continental crust, the brittle-ductile transition occurs at temperatures of roughly 300–400 °C (Tullis and Yund, 1977).

The majority of postdepositional burial experienced by the Kailas Formation was likely driven by northward movement along the Great Counter Thrust. The wide discrepancies in physical deformation and temperature history along strike suggest that the amount of tectonic and/or depositional burial varied significantly along strike and suggest that displacement along the Great Counter Thrust and/or the thickness of the hanging wall was highly variable, or that slip was partitioned differently along the India-Asia suture zone.

Implications for Slab Dynamics

Based on comparisons with other continental rift basins, it is likely that the formation of the Kailas basin resulted from modest (<5–10 km) horizontal extension (Morley, 1988; Ebinger, 1989; Schlische and Olsen, 1990; Schlische, 1992). Extension of this magnitude can be produced by a variety of local factors in a variety of tectonic settings. Although the magnitude of Kailas extension does not alone demand a plate-scale driving mechanism, the formation of this basin over ~1300 km suggests that subsidence was driven by plate-scale processes.

Formation of the Kailas basin was attributed by DeCelles et al. (2011) to rollback of the subducted Indian slab based on several lines of evidence: (1) The along-strike continuity of the Kailas Formation suggests that the mechanism driving subsidence must have been regional in scale; (2) spatio-temporal analysis of magmatic patterns north of the India-Asia suture zone reveals a 600 km southward sweep in magmatism between 32 Ma and 25 Ma (for western Tibet), a pattern similar to slab rollback processes documented elsewhere (e.g., Humphreys, 1995); (3) a pulse of adakitic and high-K magmatism across the Lhasa terrane at 25–20 Ma suggests slab breakoff (e.g., Maheo et al., 2002; Chung et al., 2003; Williams et al., 2004; Gao et al., 2007; Zhang et al., 2014); and (4) tomographic studies infer large, high-velocity zones in the mantle beneath Tibet as representing two separate, foundered slabs, one related to initial collision, and a second potentially linked to Oligocene–Miocene rollback followed by slab breakoff (e.g., Replumaz et al., 2010a, 2014).

Slab rollback processes beneath Tibet must be distinguished from oceanic slab rollback processes documented in the Mediterranean region (e.g., Jolivet and Brun, 2010; Jolivet et al., 2013) and continental slab rollback processes to explain anomalous subsidence in the Alpine foreland basin (Schlunegger and Kissling, 2015). In these cases, slab rollback refers to movement of a slab through the mantle opposite the direction of subduction.

In contrast, the mantle anomalies interpreted as the remnants of Oligocene–Miocene breakoff in southern Tibet are currently located ~800 km south of the India-Asia suture zone (Replumaz et al., 2010a, 2014). This indicates that, unlike subduction zones in the eastern Mediterranean, the India-Asia subduction zone has experienced overall trench advance relative to the mantle. As such, slab processes within the India-Asia system should be viewed as subducted slabs anchored in the mantle being “peeled” or “sheared” southward and broken off as both India and Asia moved northward relative to the mantle (van der Meer et al., 2010; Doubrovine et al., 2012; GPlate reconstructions by Douwe van Hinsbergen, http://www.geologist.nl/). The implication of this is that slab “shearing” would not necessarily alter the net postcollision north-south contractual regime within Tibet, and slab shearing would not be expected to produce a large (>100 km) zone of extension behind the shearing slab as is observed in traditional slab rollback systems (Wortel and Spakman, 2000; Brun and Facenna, 2008; Jolivet et al., 2013). However, we propose that just prior to final slab breakoff, the shearing Indian slab would have caused a short-lived episode of trench retreat as the slab exerted a downward and southward pull on the unsubducted Indian continent. This episode would have lasted no more than a few million years, but it could have resulted in enough extension in southern Tibet to drive Kailas basin subsidence. After slab breakoff, the trench would have returned to an advancing state, and an overall contractual deformation regime would have been reestablished within the India-Asia suture zone.

If the subsidence that accommodated Kailas Formation sedimentation was driven by Indian slab shearing and breakoff, the timing of Kailas Formation deposition should provide an independent record of where and when this process occurred. Data presented in this study show that the Kailas Formation in western Tibet is several million years older than in central Tibet (Fig. 14A); The Kailas Formation was deposited between ca. 26 Ma and ca. 23 Ma in the Mt. Kailas region (DeCelles et al., 2011; S. Li et al., 2015); the lower member of the Kailas Formation was deposited at ca. 24 Ma in the Yagra Valley (Carrapa et al., 2014); the upper member of the Kailas Formation was deposited at ca. 23 Ma near Lazi; and the lower member of the Kailas Formation was deposited at ca. 23 Ma near the town of Dazhuka, the easternmost site in this study. Based on
these age constraints and on the average rate of Kailas sedimentation documented near Mt. Kailas of 0.5 mm/yr (DeCelles et al., 2011), the onset of Kailas deposition migrated eastward along the India-Asia suture zone at ~300 mm/yr (Fig. 14).

The magmatic record also shows an eastward younging trend. High-K and adakitic forms of magmatism, which have been interpreted to follow slab breakoff, are older in western Tibet than in central and eastern Tibet (Ding et al., 2003; Williams et al., 2004; Liu et al., 2014). The onset of ultrapotassic magmatic activity propagated eastward at a rate comparable to that of Kailas basin sedimentation (Fig. 14). The rate of propagation is well within the rates of lateral propagation for slab tearing documented in other collisional settings (Meulenkamp et al., 1996; van der Meulen et al., 1999). The onset of adakitic and ultrapotassic magmatism lagged behind basin initiation by several million years, consistent with an expected delay between slab shearing and tearing.

The fact that slab breakoff occurred earlier in western Tibet is also supported by tomographic studies beneath the India-Asia suture zone. These show a high-velocity zone below modern India that has been interpreted as remnant of a foundering Indian continental slab (Van der Voo et al., 1999; DeCelles et al., 2002; Li et al., 2008; Replumaz et al., 2010a, 2010b). Beginning around 75°E, this high-velocity zone shallows eastward, which Replumaz et al. (2010a) interpreted as evidence for eastward progression of slab tearing.

Tearing of the Indian slab would likely have resulted in a change from extensional deformation (“soft collision” of DeCelles et al., 2011) to north-south convergent deformation (“hard collision”) within the India-Asia suture zone and southernmost Lhasa terrane as trench advance resumed. DeCelles et al. (2011) interpreted a shift in paleocurrent directions and provenance in the upper Kailas Formation in western Tibet to reflect this change through displacement along the Great Counter Thrust. In the central suture zone, the syn-convergent Liuqu Conglomerate, deposited at ca. 20 Ma (Leary et al., 2016; G. Li et al., 2015), indicates that the India-Asia suture zone and southernmost Lhasa terrane had returned to a north-south convergent regime by at least 20 Ma (Fig. 15).
Figure 15. Schematic diagrams showing the tectonic evolution of the India-Asia suture zone (IAS). Boxes show two-dimensional north-south cross sections of the central suture zone. (A) Following India-Asia collision, the Indian continental slab is underthrust beneath the Lhasa terrane, driving magmatism northward. (B) Beginning around 35 Ma, Indian slab shearing causes the southward migration of magmatism, as well as formation of the Kailas basin (KB) in the India-Asia suture zone. (C) Beginning around 25 Ma, a tear initiates along the edge(s) of the Indian slab, producing rapid subsidence followed by uplift. This also initiates a pulse of ultrapotassic and adakitic magmatism in the southern Lhasa terrane. Both of these processes follow the slab tear and migrate toward the center of the suture zone. (D) Around 20 Ma, the Indian slab breaks off completely, and the contractional deformation resumes in the suture zone. The Liuqu Conglomerate (LC) is deposited in the central suture zone in a wedge-top position within the Great Counter Thrust (GCT) system. GA—Gangdese arc; KB—Kailas basin; XF—Xigaze forearc.
Beginning at ca. 16 Ma in southwestern Tibet (83.5°E) and ca. 11 Ma near Lhasa (90°E), east-west extensional deformation rapidly accelerated (Styron et al., 2015). This is interpreted to have been driven by thickening of the lower crust in response to underthrusting of the Indian slab (Styron et al., 2015). The cessation of high-K and adakitic magmatism in southern Tibet roughly coincides with this pattern: Near Mount Kailas, magmatism began around 25 Ma and shut off around 15 Ma; north of the Lazi locality, magmatism initiated around 18 Ma and ceased around 9 Ma. This termination was likely driven by Indian plate underthrusting cutting off the asthenospheric heat source that drove melting (Chung et al., 2003). Together, the Kailas sedimentary record, magmatic record, east-west extensional record, and tomography data all support the hypothesis that the Oligocene–Miocene tectonic evolution of southern Tibet was driven by Indian slab dynamics.

Regional Implications

Based on the younging of adakitic magmatism from the eastern syntaxis to the central India-Asia suture zone, Zhang et al. (2014) proposed that slab tearing (and initial “rollback”) proceeded in the opposite direction, from east to west (Fig. 14). Zhang et al. (2014) also showed the younging trend from west to east observed in this study, but they did not interpret it. When all available data are presented (Fig. 14), it is evident that the onset of adakitic and ultrapotassic magmatism was earliest near the syntaxes and latest around 90°E. The onset of adakitic and ultrapotassic magmatism near the edges of the India-Asia suture zone and the progressive movement of that activity inward along strike raise the possibility that slab shearing and breakoff could have proceeded inward from both edges of the Indian slab.

If slab shearing and tearing commenced near the eastern and western syntaxes and progressed toward the central India-Asia suture zone, we would expect the age of the Kailas basin to match the magmatic pattern that was the basis of the interpretation made by Zhang et al. (2014). New age constraints reported by S. Li et al. (2015) and Kong et al. (2015) for the eastern Kailas Formation (locally the Luobusa conglomerate) provide a preliminary test of this idea: Detrital zircon U-Pb data reported by S. Li et al. (2015) yielded maximum depositional ages of 23 ± 1 Ma (five grains; sample 2013LBS17) and 24 ± 3 Ma (three grains; sample 2013LBS19). U-Pb analyses of zircons from an interbedded tuff in the upper portion of the Kailas Formation ~50 km east yielded an age of 18.7 ± 2.0 Ma (Kong et al., 2015). These data leave open the possibility that the basal Kailas Formation in this area may be slightly older than in the central suture zone; however, testing this hypothesis will require much more detailed age constraints.

CONCLUSIONS

The Oligocene–Miocene Kailas Formation exposed along the southern margin of the Lhasa terrane was deposited in alluvial-fan and fluvial environments within an extensional basin setting. This study provides new constraints on the depositional age of the Kailas Formation in this region and shows that its depositional age becomes younger to the east between 81°E and 90°E. The Kailas Formation near Mt. Kailas was deposited between 26 Ma and 23 Ma; deposition near Lazi occurred between ca. 25 Ma and 23 Ma; and deposition near Dazhuka occurred between 23 Ma and 22 Ma.

Based on similarities between the temporal-spatial patterns of Kailas sedimentation and ultrapotassic and adakitic magmatism in southern Tibet, we suggest that Kailas basin formation was driven by Indian slab shearing and breakoff that initiated in western Tibet and proceeded eastward. An east-to-west younging trend in adakitic magmatism between 91°E and 95°E and preliminary geochronologic constraints on the age of the Kailas Formation in this region raise the possibility that slab shearing and breakoff may have also initiated near the eastern syntaxis and propagated westward. However, more geochronologic work is required to fully test this hypothesis.

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