AGU PUBLICATIONS

Tectonics

RESEARCH ARTICLE
10.1002/2013TC003469

Key Points:
- Thick crust or high elevation in Asia prior to collision leads to mass imbalance
- A 23–29 km thick crust in India and Asia precollision eliminates mass imbalance
- Redistribution of mass at depth needed to reconcile shortening and convergence

Correspondence to:
P. V. Yakovlev,
petryak@umich.edu

Citation:
Yakovlev, P. V., and M. K. Clark (2014), Conservation and redistribution of crust during the Indo-Asian collision, *Tectonics*, *33*, 1016–1027, doi:10.1002/2013TC003469.

Received 19 OCT 2013
Accepted 30 APR 2014
Accepted article online 6 MAY 2014
Published online 10 JUN 2014

Conservation and redistribution of crust during the Indo-Asian collision

Petr V. Yakovlev[1] and Marin K. Clark[1]

[1]Department of Earth and Environmental Sciences, University of Michigan, Ann Arbor, Michigan, USA

Abstract We evaluate the mass balance of the Indo-Asian orogen by reconstructing the Indian and Asian margins prior to collision using recently published paleomagnetic and surface shortening constraints, and subtracting modern crustal volumes derived from gravity inversions and deep seismic soundings. Results show a ~30% deficit between original and modern orogen volumes if the average global crustal thickness of 41 km is assumed prior to collision, even once eastward extrusion and crustal flow are considered. Such a large discrepancy requires crustal recycling of a magnitude that is greater than one half of the modern orogenic mass, as others have previously suggested. Proposals for extensive high elevations prior to or soon after the collision further exacerbate this mismatch and dramatically increase the volume of material necessary to be placed into the mantle. However, we show that this discrepancy can be eliminated with a 23–29 km thick crust within the orogen prior to collision along with a thick southern Tibet margin (the Lhasa and Qiangtang terranes). Because of the relatively low magnitude of surface shortening in Asia, an initially thin crust would require underplating of Indian crust in southern Tibet and displacement of a highly mobile lower crust to the north and east in order to explain modern crustal thicknesses. The contrast between a proposed thinner Asian interior and older and thicker lithosphere of the North China block may have defined the distal extent of deformation at the time of collision and since.

1. Introduction

Collisional plate margins induce deformation for hundreds to over a thousand kilometers inboard of the plate boundary as a consequence of plate convergence. During the past three decades, study of the Tibetan Plateau has served as a natural laboratory for numerous descriptions of postcollisional topographic growth and their relation to geodynamic processes [*Tapponnier et al.*, 1982, 2001; *England and Houseman*, 1988; *Molnar et al.*, 1993; *Clark and Royden*, 2000; *DeCelles et al.*, 2002]. Fundamentally, these studies attempt to provide a mechanism by which ~2500 km of India's northward motion has been accommodated by continental deformation since the ~50 Ma collision with Asia [e.g., *Garzanti and Van Haver*, 1988; *Liebke et al.*, 2013]. While these studies vary in terms of rheology and degree of coupling between the crust and mantle lithosphere, it is generally thought that India acts as a rigid indenter moving northward into the weaker southern margin of Asia, which accommodates the bulk of convergence. Deformation within the Indian plate is limited to its precollisional thinned northern margin now represented by the Himalaya, while crust in the southern margin of Asia has thickened to ~2× normal thicknesses within the Tibetan Plateau.

Recently, paleomagnetic studies from terrestrial sedimentary and volcanic rocks have confirmed that less than half of the overall Indo-Asian convergence since collision is accommodated by shortening within Asia [e.g., *Dupont-Nivet et al.*, 2010; *van Hinsbergen et al.*, 2011b; *Cogne et al.*, 2013], which is consistent with structural reconstructions of the upper crust that observe low magnitude strain or crustal shortening that is limited in geographical extent [e.g., *Yin et al.*, 2008; *Li et al.*, 2011, Figure 1]. These findings present a paradox: the southern Asian continental margin had to be relatively thick prior to collision if low amounts of shortening within Asia led to modern crustal thicknesses [e.g., *Lease et al.*, 2012], but thick precollisional crust would require the removal of crustal mass in excess of its modern volume in order to accommodate ~2500 km of continental convergence since collision [*Molnar and Stock*, 2009; *Dupont-Nivet et al.*, 2010; *Cogne et al.*, 2013]. The missing crustal mass or "mass deficit" is made larger if regions of high crustal thickness in Asia existed prior to or soon after collision, as suggested by estimates of precollisional crustal shortening [e.g., *Murphy et al.*, 1997; *Kapp et al.*, 2007b] and high-standing early Cenozoic paleoelevation estimates for the northern and eastern Tibetan Plateau [*Rowley and Currie*, 2006; *Quade et al.*, 2011; *Bershaw et al.*, 2012; *Hoke et al.*, 2014].

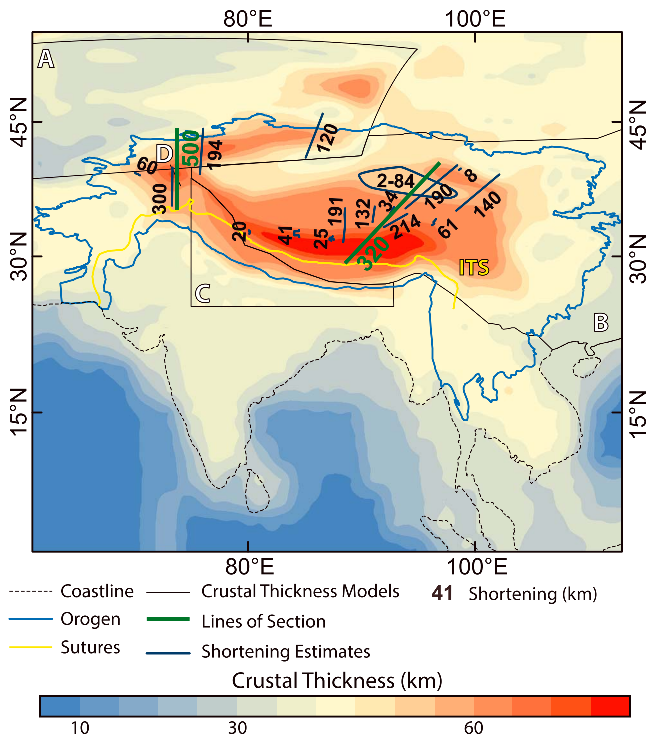

Figure 1. Crustal thickness model and outline of the Indo-Asian orogen. Regional crustal thickness reconstructions used in our interpolation: (a) *Steffen et al.* [2011], (b) [*Zhang et al.*, 2011b], (c) [*Zhang et al.*, 2011a], and (d) *Mechie et al.* [2011]. Crustal thicknesses in all other areas estimated from interpolation of the Crust 2.0 model [*Bassin et al.*, 2000]. Currently available upper crustal shortening estimates for Tibet totaling ~320 km of north-south shortening in eastern Tibet and ~500 km in the Pamir and Tien Shan along the lines of section shown. A summary of values and sources can be found in Table 2. ITS – Indus-Tsangpo Suture.

Calculations of mass deficit are sensitive to the approximation of collision age because of the rapid northward velocity of India near ~ 50 Ma (90–150 mm/yr) [e.g., *Molnar and Stock*, 2009; *van Hinsbergen et al.*, 2011a]. Previously published mass balance calculations [*Le Pichon et al.*, 1992; *Replumaz et al.*, 2010] are based on a 45 Ma collision age, which is younger than the canonical age of 55–50 Ma supported by sedimentary evidence [e.g., *Garzanti and Van Haver*, 1988; *Sciunnach and Garzanti*, 2012]. More recently published, albeit controversial, studies suggest a much younger age for collision at 34 Ma [*Aitchison et al.*, 2007] or even 25–20 Ma [*van Hinsbergen et al.*, 2012]. These collision ages would strongly influence the assumed mass input, with the total net convergence for a younger (or older) collision decreasing (or increasing) the total volume of mass added to the orogen.

In an attempt to resolve the mass balance problem, several earlier studies appeal to methods by which mass was removed from the orogen since ~50 Ma. Proposed solutions include the eastward extrusion of Asian affinity crustal blocks [*Tapponnier et al.*, 1982; *Le Pichon et al.*, 1992; *Replumaz and Tapponnier*, 2003] and recycling of Indian [*Le Pichon et al.*, 1992; *van Hinsbergen et al.*, 2012] or Asian [*Tapponnier et al.*, 2001] crust into the mantle. In this study, we evaluate these and other processes affecting calculations of crustal volumes, which have not been previously quantitatively considered, including that an Andean style, thick crust existed beneath the southern Tibet prior to collision [*Murphy et al.*, 1997; *Kapp et al.*, 2007b]. We incorporate published extrusion values based on tomography and plate reconstructions [*Leloup et al.*, 1995; *Replumaz and Tapponnier*, 2003], lower crustal flow into eastern Tibet [*Clark and Royden*, 2000], and new estimates of modern crustal thicknesses [e.g., *Steffen et al.*, 2011; *Zhang et al.*, 2011b] (Figure 1). In order to avoid uncertainties associated with a precise collision age, we use independent estimates of Asian shortening [*Dupont-Nivet et al.*, 2010] and the size of the precollisional Indian subcontinent [*Gibbons et al.*, 2012] to constrain the crustal volume input (Figure 2). However, these are generally compatible with the 2000–2500 km of Indo-Asian convergence observed since 40 Ma [*van Hinsbergen et al.*, 2011a], a collision age suggested by *Bouilhol et al.* [2013]. We also calculate precollisional crustal thicknesses for Asia and India assuming that crustal volume is conserved in order to test the viability of a thin precollisional crust as an alternative to crustal recycling.

2. Methods

We investigate the mass balance of the Indo-Asian orogen by first defining the extent of the orogen and calculating its volume based on a compilation of published geophysical estimates of crustal thicknesses plus the total stored eroded volume in sedimentary basins surrounding the orogen. We then calculate the Indian and Asian components of areal input during collision from published paleomagnetic data sets [*Dupont-Nivet et al.*, 2010; *Gibbons et al.*, 2012] with and without components of eastward extrusion. Next, we subtract the input crustal volume by multiplying the areal input by a global average for crustal thickness (~41 km) with or

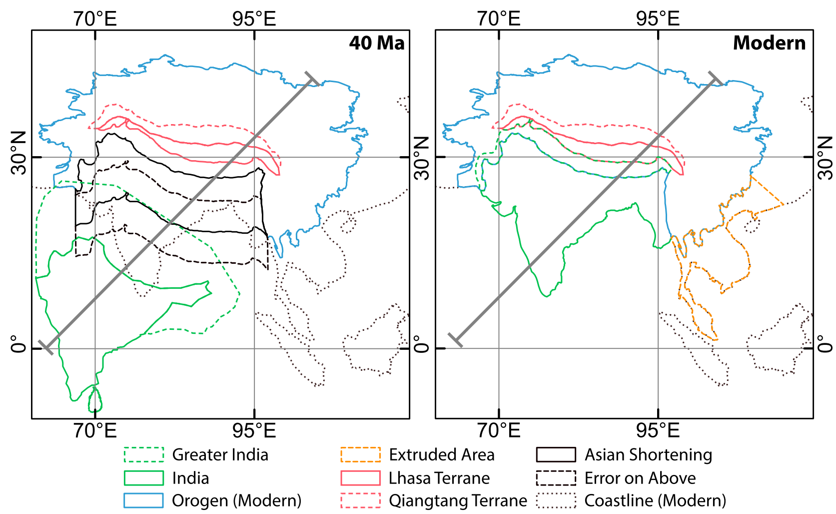

Figure 2. Input areas for our calculations. Greater India is derived from *Gibbons et al.* [2012] with position at 40 Ma using their paleomagnetic reconstruction and a stable Eurasia in GPlates [*Williams et al.*, 2012]. Asian shortening estimates are from *Dupont-Nivet et al.* [2010], with the ITS moved directly south to define an area. Areas of possible precollisional crustal thickening are outlined in red. A schematic estimate of extruded material is in dashed orange. Note that this is not meant to show specific areas that were extruded from the collision with India but rather to illustrate the relative magnitude of this process. Gray lines indicate sections used in Figure 4.

without a thicker, Andean-style margin for southern Eurasia. Finally, we use the modern orogenic volume to estimate the precollisional crustal thicknesses in India and Asia that would be compatible with orogen-scale mass conservation.

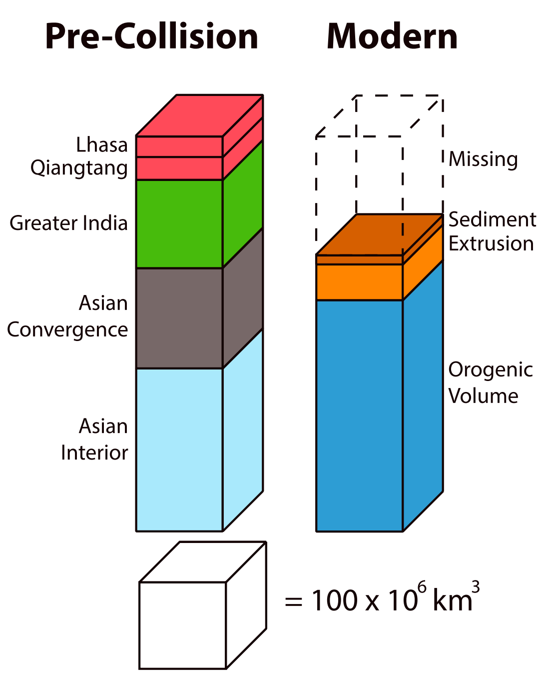

Figure 3. Diagram of mass balance results, assuming 60 km thick Lhasa and Qiangtang terranes, and 41 km thick crust elsewhere prior to collision. We use Asian shortening values of *Dupont-Nivet et al.* [2010] and size of India from *Gibbons et al.* [2012]. The volume of each rectangular prism is scaled to accurately represent the volume of each component.

2.1. Calculating Modern Volumes

In order to investigate the balance between input and modern volumes (Figure 3), we first define the extent of the Indo-Asian orogen in the modern. This allows us to clearly delineate regions that were thickened during collision and must have increased in mass due to input from Indian or Asian shortening. We define the areal limits of the modern orogen using the extent of high modern strain rates and/or postcollisional crustal thickening (Figure 2) and use crustal thicknesses determined from geophysical data for this region to estimate the modern crustal volume (Figure 1). We estimate the northeastern extent of the Indo-Eurasian orogen at approximately ~40°N and the northwestern boundary north of the Tien Shan, which define the position of a relatively stationary northern boundary since the time of collision [*Clark*, 2012] and the modern limit of concentrated strain, respectively. Following the region of high GPS velocities in the Asian interior that correlates with regions of high topography [*Gan et al.*, 2007] and crustal thickening, we use the 1000 m contour in the western half of the orogen. This relationship is more ambiguous in eastern Tibet, where we follow the 500 m contour due to the more diffuse nature of topography in that

Table 1. Comparison of Our Study With Previous Work (in Units of 10^6 km^2)

Variable	This Study	*Le Pichon et al.* [1992]	*Replumaz et al.* [2010]
Area of Asia (collision)	11.5 ± 1.8	14.6	15[a]
Area of Asia (modern)	7.9	10.7	10.3[a]
Change in Asian area	3.6 ± 1.8	3.9[a]	4.7
Area of Greater India (collision)	4.2 ± 0.4[c]	1.6–2.5[a]	3.1
Area of Greater India (modern)	-	-	0.8
Extrusion	0.8 - 2.1	-	-
Net area prior to collision	15.7 ± 1.8	16.2–17.1	18.1
Modern volume (*10^6 km^3)	390 ± 80[c]	530[a,c]	480[b,c]
Sediment volume	17[c]	-	22[c]
Area of Lhasa Terrane	0.58	-	-
Area of Qiangtang Terrane	0.64	-	-

[a]Values not explicitly stated and derived via methods described in text.
[b]Excludes volumes of sediment moved out of the orogen.
[c]Units are of 10^6 km^3.

region and ambiguity between small amounts of post and precollisional thickening. The southern and southeastern boundaries are in turn defined by the Main Frontal Thrust in India and the Sagaing Fault in Burma, respectively.

Our definition differs from previous studies [*Le Pichon et al.*, 1992; *Replumaz et al.*, 2010], which include the Altai in the definition of the Indo-Asian orogen. We recognize that large historic earthquakes and Quaternary fault slip occur farther north within the Gobi corridor (Mongolia) [*Baljinnyam et al.*, 1993; *Cunningham*, 2013]. However, Cenozoic shortening in the Altai did not begin until Pliocene time [e.g., *Tapponnier and Molnar*, 1979; *De Grave and Van den haute*, 2002; *Glorie et al.*, 2012] and must account for a negligible amount of the overall convergence between India and Eurasia; and consequentially, the modern crustal thickness of up to 50 km in this area [*Zorin et al.*, 1990] is difficult to wholly attribute to India-Asia collision and may in part be attributed to Mesozoic mountain building events. Further, our chosen extent omits large regions of Indonesia incorporated by *Replumaz et al.* [2010], as the inclusion of significant regions of oceanic crust will skew input estimates based on continental crustal volumes.

We use two compilations to derive crustal thicknesses from seismic soundings, gravity inversion and surface wave tomography, one extending over Tibet and the Himalayan front [*Zhang et al.*, 2011a] and another covering China [*Zhang et al.*, 2011b]. We further incorporate a published gravity inversion model of the Tien Shan [*Steffen et al.*, 2011], seismic refraction data from the Pamir [*Mechie et al.*, 2011], and use the CRUST 2.0 global model [*Bassin et al.*, 2000] where higher resolution data are not available. Due to significant discrepancies between the individual data sets, they are clipped to their primary areas of focus, with individual extents shown in Figure 1. We approximate a one sigma uncertainty in Moho depths for our model as 5 km, based on uncertainties reported in the data sources. Finally, we add the volume of material eroded from the orogen since collision, by combining the solid phase volume held in the Indus, Ganges, Pakistan, Bengal, and Andaman basins, as well as the Gulf of Thailand since 58 Ma [*Métivier et al.*, 2002].

In lieu of making blanket assumptions of crustal density profiles for the orogen in order to evaluate crustal mass, we note that typical density contrasts are sufficiently small to be neglected. The ~7% density difference between upper crustal rocks (e.g., granite) and the granodiorite or granulite compositions typically inferred for the lower crust [e.g., *Jackson*, 2002; *Burov and Watts*, 2006] would only change resulting estimates of the modern orogenic mass by ~5% if localized to depths beneath 35 km. As such, we use the terms "mass" and "volume" interchangeably, with all input and modern volumes assumed to have homogenous densities at the orogen scale.

2.2. Estimating Crustal Volume Prior to Collision

We derive the input volume to the orogen from the extent and thickness of precollisional India and Asia separately minus geological constraints on eastward extrusion. Material that is extruded eastward absorbs net convergence but does not contribute to the modern orogen volume so it is subtracted from the areal input (Table 1). Input volumes are based on the areal extent of India determined from marine magnetic anomalies [*Gibbons et al.*, 2012] (Table 1), and the areal extent of Asia determined both from paleolatitude

Table 2. Crustal Shortening Estimates Used in This Study

Location	Source	Shortening (km)[a]	Azimuth
Pamir	*Burtman and Molnar* [1993]	300	-
Tien Shan	*Avouac et al.* [1993]	194	16
Tien Shan	*Avouac et al.* [1993]	120	3
Peter the First Range	*Hamburger et al.* [1992]	60	40
Lhasa block	*Kapp et al.* [2003]	20	5
Qiangtang	*Kapp et al.* [2005]	41	2
Qiangtang	*Kapp et al.* [2005]	16	0
Qiangtang	*Kapp et al.* [2007a]	25	0
Lhasa and Qiangtang	*Wu et al.* [2012]	191	-
Songpan-Ganzi	*Li et al.* [2011]	132	6
Songpan-Ganzi	*Li et al.* [2011]	214	50
Hoh Xil Basin	*Wang et al.* [2002]	34	30
Yushu-Nangqian	*Spurlin et al.* [2005]	61	45
Northeast Tibet	*Meyer et al.* [1998]	140	42
Northeast Tibet	*Meyer et al.* [1998]	190	44
Qilian Shan	*Zheng et al.* [2010]	8	38
Qaidam basin	*Yin et al.* [2008]	1.6–50	-
Qaidam basin	*Liu et al.* [2009]	19–60	-
Qaidam basin	*Zhou et al.* [2006]	1–18	-

[a]In cases where a cross section is composed of multiple segments, the longer section is used.

estimates from paleomagnetism of continental volcanic and sedimentary rocks [*Dupont-Nivet et al.*, 2010; *Sun et al.*, 2010; *Tan et al.*, 2010; *Cogne et al.*, 2013] and palinspastic reconstructions of upper crustal shortening (Table 2). By using geologic constraints for the original continental geometry of India and Asia, we avoid reliance on determining a precise collision age in order to determine the total net convergence.

In estimating mass balance and precollisional crustal thicknesses, we assume that a 60 km thick crust existed beneath southern Tibet (Lhasa and Qiangtang terranes) as has been suggested by >40–60% of Cretaceous shortening in the two terranes [*Murphy et al.*, 1997; *Kapp et al.*, 2007b]. For other regions within the orogen, we use a precollisional thickness equal to the global average 41 km thick crust [*Christensen and Mooney*, 1995] as a reference value. However, we note that some authors have proposed that northern Tibet may have been ≥ 4 km high [e.g., *Rowley and Currie*, 2006], or that eastern Tibet may have been 45 ± 5 km thick [*Lease et al.*, 2012], suggesting that using crustal thickness values from the global average may underestimate crustal input.

2.2.1. Input Volume From India

To determine the areal input of India, we use the Greater India of *Gibbons et al.* [2012] who follow previous authors [e.g., *Ali and Aitchison*, 2005] in defining the northern extent of India by the Zenith and Wallaby plateaus, and incorporate a newly discovered Jurassic sliver of oceanic crust now isolated in the Indian Ocean. The resulting geometry extends Greater India ~1100 km past the modern extent of the subcontinent, yielding an

Table 3. Mass Balance Calculations for Alternative Reconstructions of Asia Based on Paleomagnetic Data and Our Compiled Upper Crustal Shortening Estimates

Author	Asian Shortening	Areal Input ($\times 10^6$ km^2)	Crustal Thickness[a]	Mass Deficit ($\times 10^6$ km^3)[a]
Dupont-Nivet et al. [2010]	1100 km	3.6	23–27 km	190–260
Tan et al. [2010]	810 km	2.8	24–29 km	160–230
van Hinsbergen et al. [2011b]	600 km/1050 km[c]	1.9	26–31 km	120–190
Sun et al. [2012]	1700 km	5.9	20–23 km	290–360
Cogne et al. [2013]	1450 km	4.4	22–26 km	220–290
van Hinsbergen et al. [2012]	600 km/1050 km[c]	1.9	30–36 km[b]	50–120[b]
This paper	320 km/500 km[c]	1.3	27–33 km	100–170

[a]Crustal thickness of Asia and Greater India prior to collision required if mass is conserved. Range stated is for cases with 60 km thick Lhasa and 60 km Lhasa and Qiangtang, as in columns 2 and 3 of Table 4. Errors on crustal thickness are typically 5–6 km with 2σ uncertainty.
[b]Calculated using input of India (2.5 x 10^6 km^2) from *Van Hinsbergen et al.* [2012].
[c]Calculated for two cross-sections in the west and east of the orogen, respectively.

Table 4. Average Crustal Thicknesses Necessary to Balance Modern Volume Using Asian Convergence Estimates of *Dupont-Nivet et al.* [2010] and Greater India of *Gibbons et al.* [2012]

	No Lhasaplano	60 km Lhasa	60 km Lhasa and Qiangtang
No extrusion	26 ± 5 km	25 ± 5 km	23 ± 6 km
Extrusion	29 ± 6 km	27 ± 6 km	26 ± 6 km

area of ~4.2×10^6 km^2. We add a 10% error to this estimate in order to account for proposals of a late Cretaceous island arc collision with northern India [e.g., *Reuber*, 1986; *Jagoutz et al.*, 2009], and any magmatic addition to continental crust added during extension, typically thought to be < 4 km in width [*Buck*, 2006].

2.2.2. Input Volume From Asia

Reconstructing the areal extent of Asia is accomplished from changes in paleolatitude or undoing shortening values associated with upper crustal deformation. We use the paleomagnetic estimate of post-Cretaceous convergence within Asia of 1100 ± 500 km from the Linzizong volcanic sequence in the Lhasa terrane [*Dupont-Nivet et al.*, 2010] as a median point of reference. While this estimate is one of many published over the last several years, it accounts for known problems with inclination shallowing and averaging of secular variation found in many previously published data sets that may overestimate convergence values. However, we also tested several convergence estimates from other recent publications (Table 3).

We further consider published palinpastic reconstructions of the Tibetan interior from structural geology studies, which reflect the portion of convergence recorded by upper crustal shortening in Asia (Figure 1). We assume a 50% uncertainty in stratigraphic thicknesses, which is likely given the typically low number of stratigraphic measurements in a given map area and heterogeneities in crustal thickness within intermontane basins. Under area-balancing considerations, such uncertainties directly translate to a ~50% shortening error, which we apply to all palinspastic reconstructions of deformed sedimentary strata in Tibet (Table 2). We compile these data along two lines of section: through the Pamir and Tien Shan in the west, and from Indus-Yarlung Suture to the Qilian Shan in the east (Figure 1).

Using the Indus-Tsangpo suture as the surface boundary between Asian and Indian affinity crust [e.g., *Gansser*, 1964] and a comparable suture zone in Pakistan as defined by *Ahmed and Ernst* [1999], we translate Asian shortening estimates into those of areal input by a generally southward migration of the suture. Our compilation of Asian upper crustal shortening estimates yields ~500 ± 250 km and ~320 ± 160 km of north-south upper crustal shortening at the west, and east ends of the orogen, respectively (Figure 1). These lie at or below the lower limit of convergence determined from paleomagnetism (Table 3). Uncertainties in shortening budgets are likely owed to a lack of subsurface and stratigraphic control across extensive regions and understudied regions potentially account for the lower total shortening value from cross sections compared to the paleomagnetic data.

Another contribution in estimating the areal input into the orogen is the possibility of extrusion of large crustal blocks [*Tapponnier et al.*, 1982; *Leloup et al.*, 1995; *Replumaz and Tapponnier*, 2003] from the interior of the orogen to areas outside its margins. We obtain an upper bound of net extrusion area since collision from estimates by *Replumaz and Tapponnier* [2003] under the assumption that rates have remained constant between 40 and 50 Ma. However, the large displacements on strike-slip faults used in this work have been challenged by other authors [e.g., *Cowgill*, 2007; *Leloup et al.*, 2011; *van Hinsbergen et al.*, 2011b]. As such, we define the lower bound for extrusion from the value proposed by *Leloup et al.* [1995] to obtain the range of 0.8–2.1 × 10^6 km^2 used in our calculations. As this is still an order of magnitude greater than that suggested by *Van Hinsbergen et al.* [2011b] (which amounts to ~ .1 × 10^6 km^2, using our definition of the boundaries of the orogen), we also include cases with no extrusion in our estimates of precollisional crustal thicknesses (Table 4). Using the larger estimate of *Replumaz and Tapponnier* [2003] alone would decrease the mass input slightly, leading to only a 7% increase in estimated crustal areal input because more crust is extruded eastward.

3. Results

Given the above constraints, our volume balance calculation is simply the volume input, defined by the net area prior to collision times the global average crustal thickness (41 km), minus the modern orogen volume, which includes the modern orogen volume plus the eroded volume preserved in sedimentary basins surrounding the orogen. In cases where extrusion is considered, the extruded area is subtracted from the net area prior to collision. Under this assumption of average crustal thickness, the input volume due to the convergence between Asia and India is greater than the volume of crust present within the orogen, yielding an overall mass deficit in the modern (Table 3). For example, using the median paleomagnetism estimate [1100 ± 500 km, *Dupont-Nivet et al.*, 2010], assuming a 60 km thick Qiangtang and Lhasa terranes, with 41 km thick crust in the remainder of the orogen and including extrusion yields a deficit of 200×10^6 km^3 or ~30% less crust in the modern than expected to have been present prior to collision based on our calculated volume input (Figure 3). This mass deficit value of 200 x 10^6 km^3 is more than half of the modern orogenic volume which we estimate as $390 \pm 80 \times 10^6$ km^3 based on our compilation of regional crustal thickness models (Figure 1). By comparison, using the lower Asian shortening estimates determined from upper crustal shortening (320–500 km) would produce smaller values of crustal input and correspondingly lower estimates of volume deficit (100–170 $\times 10^6$ km^3), or equivalent to about one third of the modern orogen volume. Although these lower values likely reflect an underestimate of crustal input due to unstudied regions of crustal shortening compared to the estimates of Asian shortening from paleomagnetism.

We also test a case in which mass is conserved. Instead of assuming a crustal thickness prior to collision equal to the global average, we calculate what the precollisional thickness of India and Asia must be in order to conserve crustal volume based on modern volumes divided by the precollisional area of India and Asia (Table 4). We calculate values based on a uniform thickness, as well as the case where the southern Asian margin is thickened prior to collision (Qiangtang and/or Lhasa block) and additionally consider cases with extrusion and where extrusion was negligible ("No Extrusion"). In order to conserve crustal volumes, the Indian and Asian crust would have needed to be ~23–29 km thick prior to collision (Table 4). Cases with no extrusion yield smaller values of 23–26 km than those including it (26–29 km). Similarly, cases which include a larger area of thick crust prior to collision require thinner crust (23–27 km) elsewhere in the orogen.

Furthermore, due to significant differences in methods and terminology between this study and previous work, we attempt to put our calculations into a common framework (Table 1). *Le Pichon et al.* [1992] use topography as an analog for crustal thickness and necessary crustal shortening, under the assumption that $T = (h \times 7) + 35$. Where T is crustal thickness and h is topographic elevation. We combine their estimates of the mean elevation and surface area of Tibet to yield an equivalent crustal volume. *Replumaz et al.* [2010] perform a density correction to reduce sediment volumes by 17%. We found a $<$ 1% change in resulting crustal thicknesses and mass imbalances for our data set when making a similar correction, and so state their sediment volumes without such correction.

Le Pichon et al. [1992] argue for 1.8–3.0 $\times 10^6$ km^2 of missing area, which would equate to 74–123 $\times 10^6$ km^3 if the crust was 41 km thick, and *Replumaz et al.* [2010] suggest a mismatch of 11–14 $\times 10^6$ km^3 of Asian and ~119–149 $\times 10^6$ km^3 of Indian crust. *Le Pichon et al.* [1992] suggest a modern orogenic volume that is ~36% greater than our estimate and use a Greater India that is only 385–676% of the area proposed by *Gibbons et al.* [2012]. *Replumaz et al.* [2010] suggest that the majority of mass imbalance in the orogen is due to Indian-derived crust and argue against a mass transfer beneath Tibet and in favor of recycling. However, their work implicitly transfers mass from the Indo-Asian orogen to the Altai, amounting to 8% of the overall orogenic volume, without providing a mechanism by which such a transfer could have occurred. Furthermore, our estimates incorporate published estimates of crustal extrusion away from the orogen. This is implicated as a possible solution to mass imbalance by *Le Pichon et al.* [1992] and implicitly incorporated by *Replumaz et al.* [2010]. However in the latter work, the area of the "Indochina Block" located east of the path of the eastern Himalayan syntaxis does not increase between 45 Ma and modern, indicating that overall area loss is accommodated by crustal shortening rather than extrusion.

4. Discussion

Our results show that a mass balance between modern and precollisional volumes is impossible to achieve given a global average to thick crust prior to collision (≥41 km). Such a discrepancy can be accounted for in two primary ways: (1) recycling of crustal material into the mantle or (2) a thin Indo-Asian crust prior to collision averaging ~23–29 km. Deep seismicity in the Pamir is often cited as evidence of crustal subduction [*Burtman and Molnar*, 1993], and to a limited extent, this mechanism has been proposed for Tibet based on geologic constraints [e.g., *Tapponnier et al.*, 2001]. However, we stress that the subducted volume necessary to balance an initial average thickness crust is equal to more than half the volume of crust currently within the orogen today and more than an order of magnitude greater than the ~11–14 $\times 10^6$ km^3 proposed for Asian continental subduction [*Tapponnier et al.*, 2001; *Replumaz et al.*, 2010] or the ~15×10^6 km^3 estimated for Indian underplating and eclogitization [e.g., *DeCelles et al.*, 2002; *Hetényi et al.*, 2007; *Replumaz et al.*, 2010]. Furthermore, proposals of an extensive high plateau prior to or soon after collision [*Rowley and Currie*, 2006; *Quade et al.*, 2011; *Bershaw et al.*, 2012; *Hoke et al.*, 2014] exacerbate the imbalance. If the majority of the high topography, and therefore modern crustal volume, was already in place by Eocene to Oliogocene time, then all or most of the input volume (amounting to ~ 3×10^8 km^3) would need to be recycled into the mantle. Thus, in our opinion, consideration of plate motions and crustal volume balance seriously challenge the interpretation from recent isotopic proxies for high paleoelevations in northern and eastern Tibet during Eocene and Oligocene time because these would require the recycling of an untenable amount of crustal material to the mantle.

As an alternative to crustal subduction, we hypothesize that a thin crust existed across much of the orogen prior to collision, which was likely near sea level. A thin precollisional crust is consistent with sedimentalogical, geomorphic, and paleoclimatic constraints: Greater Indian sediments were deposited below sea level during the Jurassic and remained so during its drift from Gondwana [*Sciunnach and Garzanti*, 2012]. Similarly, extensive regions in the northwest part of the orogen, encompassing the modern Tajik, Tarim, and eastern Qaidam basins, were part of an inland sea that did not reach modern elevations until Eocene or Miocene time. [*Ritts et al.*, 2008; *Bosboom et al.*, 2011] Other areas such as the modern Xining-Minhe-Lingzhong basin complex located at the northeast end of the orogen were unlikely to be at high elevations during Eocene time as evidenced by sedimentary sequences indicative of externally drained distal fluvial to lacustrine depositional environments [e.g., *Ren et al.*, 2002; *Horton et al.*, 2004]. Lastly, relict erosional surfaces at the extreme southeast end of the orogen provide evidence for generally low relief and subdued topography connected to sea level [*Clark et al.*, 2006]. A thin crust with reasonable, albeit relatively low density, and a thin mantle lithosphere could reasonably support above sea level elevations [*Clark et al.*, 2012], which would be consistent with the lack of Cretaceous age and younger marine strata within the interior of Tibet. Today, similar thin crust can be observed in Northern Ireland (24–30 km) [*Davis et al.*, 2012] and Indonesia (16–44 km) [*Macpherson et al.*, 2012]. If the regions of Asia north of Qiangtang terrane were thin prior to Indian collision, a stationary northern boundary to the plateau [*Clark et al.*, 2010; *Clark*, 2012] may be explained in part by this inherited rheologic contrast.

Our solution to the mass balance paradox is in contrast to one proposed by *Van Hinsbergen et al.* [2012] who use paleolatitudes of Indian terranes and mantle tomography to propose a microcontinent collision at ~50 Ma and subduction of oceanic crust over the next ~25 Myr, eliminating ~2300 km of continental crust from total convergence budgets. Using the methods outlined in this paper, and Asian and Indian shortening constraints from their work, we estimate that a 30–36 km crust prior to collision in areas of the orogen outside of southern Tibet would conserve crustal volume, as compared to 23–29 km using our chosen estimates from *Gibbons et al.* [2012] and *Dupont-Nivet et al.* [2010] (Table 3). However, this value will still not provide a volume balance if extensive regions of high topography existed in northern and eastern Tibet [e.g., *Rowley and Currie*, 2006; *Quade et al.*, 2011; *Bershaw et al.*, 2012; *Lease et al.*, 2012; *Hoke et al.*, 2014] despite the resulting mass imbalance being obviously smaller due to the reduction of Indian mass input (Table 3).

Thin crust in India and the Asian interior prior to collision requires a consideration of crustal shortening estimates in order to discern between viable models [*Tapponnier et al.*, 1982, 2001; *England and Houseman*, 1988; *Molnar et al.*, 1993; *Clark and Royden*, 2000; *DeCelles et al.*, 2002] for plateau development. Our compilation of Asian upper crustal shortening estimates yields a smaller value for Asian crustal input (300–500 km) than the total convergence within Asia by paleomagnetic studies [~1100–1450 km, e.g., *Dupont-Nivet et al.*, 2010; *Cogne et al.*, 2013], which suggest that Asia absorbed about half (or less) of the total convergence of India with Eurasia since ~ 50 Ma. In addition, our values are smaller than those suggested by *Van Hinsbergen et al.* [2011b] (600–1000 km) due to our reliance solely on estimates of upper crustal shortening (as opposed to incorporation of paleomagnetic estimates), lack of interpolation of shortening values across unquantified regions, and use of recently published palinspastic reconstructions in the plateau interior [e.g., *Li et al.*, 2011; *Wu et al.*, 2012]. The discrepancy between paleomagnetic estimates and those solely from upper crustal shortening values may be due to two primary factors: (1) systematic overestimates of Asian convergence from paleomagnetic data and (2) the paucity of data from the Tibetan interior, which may underestimate total crustal shortening. Recent paleomagnetic studies have begun accounting for known problems that contributed to older values of upward of ~2000 km of inter-Asian convergence [e.g., *Dupont-Nivet et al.*, 2010; *Sun et al.*, 2012] and generally agree on estimates of over 600 km [see *Cogne et al.*, 2013].

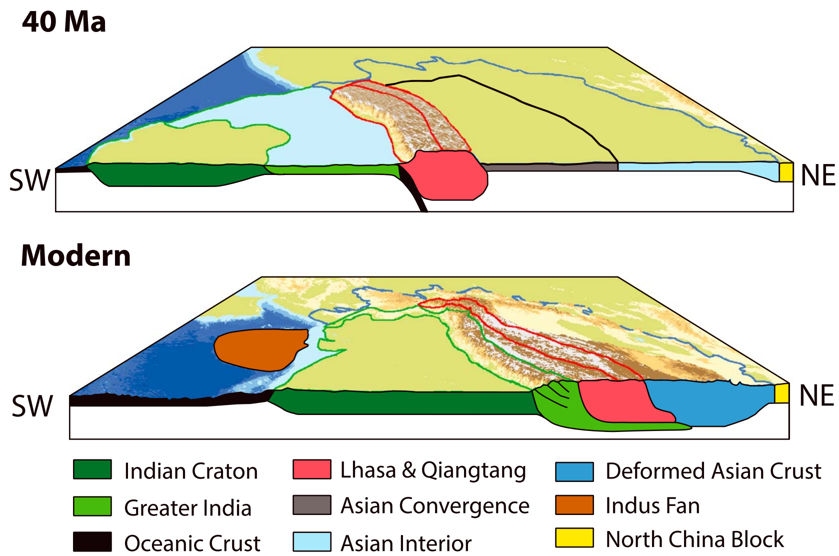

Figure 4. Geodynamic cartoon of processes and distances mentioned in text. Top shows the scenario near the time of collision, with thinned Greater India and Asian interior. The Lhasa and Qiangtang terranes are thickened prior to collision. Lower portion shows the modern state of the orogen, with convergence accommodated by Indian underthrusting, Asian shortening and lower crustal flow. Colors used are the same as in Figure 3, and lines of section are shown in Figure 2.

Our upper crustal shortening compilation contains data along nearly the complete line of section, suggesting that there are no significant data gaps. As such, additional studies are unlikely to double the current net shortening value to bring it in line with paleomagnetic estimates. In order to conserve crustal volume, low amounts of upper crustal shortening imply that more than half of the net Asian convergence had to be accommodated without being recorded in the upper crust. This is supported by evidence of a viscous lower crust, which moves material from areas of high crustal thickness near the collision boundary to thinner areas at the margins that have experienced insufficient post-Eocene shortening to bring them to modern elevations [e.g., *Clark and Royden*, 2000; *Wang et al.*, 2005; *Le Pape et al.*, 2012]. Similarly, the ~1100 km width of Greater India prior to rifting from Gondwana is greater than the 600–900 km of shortening seen in the Himalaya [*DeCelles et al.*, 2002; *Robinson et al.*, 2006; *Yin et al.*, 2009; *Long et al.*, 2011] and supports the underthrusting of Indian crust north of the Indus-Tsangpo Suture (ITS) [*Nábelek et al.*, 2009; *Ceylan et al.*, 2012; *Agius and Lebedev*, 2013] and mass redistribution at depth [*Zhao and Morgan*, 1987; *DeCelles et al.*, 2002] (Figure 4).

5. Conclusions

Current estimates from geologic and paleomagnetic records suggest that half or less of the overall Indo-Asian convergence since collision has been absorbed by Asian shortening. If average crustal thicknesses are assumed, this can directly account for doubling of Asian crust to modern values of 60–80 km, leaving nearly half of India's convergence unaccounted for in the modern mass of the orogen. Mass balance calculations with a 41 km crust and a high "Lhasaplano" at the Asian margin prior to collision yield a ~30% or ~200×10^6 km^3 mismatch between modern and input volumes for the Indo-Asian orogen. These are an order of magnitude larger than proposed estimates of Asian continental subduction and eclogitization of underthrust Indian crust [*Replumaz et al.*, 2010] and incorporate a range of extrusion values. Proposals for thick crust in northern and eastern Tibet prior to or soon after collision [*Rowley and Currie*, 2006; *Quade et al.*, 2011; *Bershaw et al.*, 2012; *Hoke et al.*, 2014] further increase the mismatch and require of order half to more than one times the modern orogenic crustal volume to be placed into the mantle. We propose that crustal conservation can be achieved with a ~23–29 km crust across the precollisional Asian interior and Greater India, with the notable exceptions of the Lhasa and Qiangtang terranes. As a direct consequence, the ~1100 km of Asian convergence suggested by paleomagnetic studies would be insufficient to build modern crustal volumes and would require addition of Indian material and mass redistribution at depth. The long-lived northern boundary of the plateau, located at ~40°N, is then the result of a rheologic contrast with older, thicker lithosphere of the North China block.

Acknowledgments
This work was supported by NSF (grants EAR0908711 and EAR1211434) and a visiting faculty fellowship from the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado, Boulder (MKC). We thank Peter Molnar and Nathan Niemi for their thorough and insightful comments on an early version of this manuscript. Nadine McQuarrie and Associate Editor Rebecca Bendick provided constructive reviews that improved the clarity of the manuscript.

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