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Key Points:
- Estimated 600–750 km postcollisional intra-Asian shortening is a minimum value
- Collision age of 52 Ma, rather than 65 Ma or 34 Ma, is preferred by our analyses
- Major extension happened between the TH and cratonic India during the Cretaceous

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Paleomagnetic tests of tectonic reconstructions of the India-Asia collision zone

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Abstract Several solutions have been proposed to explain the long-standing kinematic observation that postcollisional upper crustal shortening within the Himalaya and Asia is much less than the magnitude of India-Asia convergence. Here we implement these hypotheses in global plate reconstructions and test paleolatitudes predicted by the global apparent polar wander path against independent, and the most robust paleomagnetic data. Our tests demonstrate that (1) reconstructed 600–750 km postcollisional intra-Asian shortening is a minimum value; (2) a 52 Ma collision age is only consistent with paleomagnetic data if intra-Asian shortening was ~900 km; a ~56–58 Ma collision age requires greater intra-Asian shortening; (3) collision ages of 34 or 65 Ma incorrectly predict Late Cretaceous and Paleogene paleolatitudes of the Tibetan Himalaya (TH); and (4) Cretaceous counterclockwise rotation of India cannot explain the paleolatitudinal divergence between the TH and India. All hypotheses, regardless of collision age, require major Cretaceous extension within Greater India.

1. Introduction

The continental collision between India and Asia contributed substantially to the growth of the largest modern orogen. This collision happened along the Yarlung-Zangbo Suture Zone, which contains remnants of oceanic lithosphere (ophiolites) and accretionary mélanges [*Gansser*, 1964]. Initiation of collision is paleomagnetically defined as the time at which the latitude of the Lhasa continental block of southernmost Asia overlaps with the latitude of rocks of the Tibetan Himalaya (TH) that represents the northernmost continental crust derived from the Indian plate (Figure 1). The retrodeformed area between the former northern margin of the TH and the modern southernmost thrust of the Himalaya is commonly defined as Greater India [e.g., *Powell and Conaghan*, 1973, 1975; *Hodges*, 2000] (Figure 1).

Stratigraphic, structural, and sedimentologic data across the suture zone have for decades been interpreted to indicate an early to middle Eocene age for this initial collision [*Dewey and Bird*, 1970; *Molnar and Tapponnier*, 1975], widely cited as ~50 Ma. It quickly became clear, however, that the amount of convergence between India and Asia since this initial collision, estimated using marine magnetic anomaly and fracture zone-based reconstructions of the Indian and Atlantic Oceans (~3000 km since ~50 Ma [*Molnar and Tapponnier*, 1975; *Patriat and Achache*, 1984]), far exceeded the amount of coeval shortening documented in the Himalaya and Tibet (1000–1500 km [e.g., *Coward and Butler*, 1985; *Dewey et al.*, 1988]). In the following decades of research, these numbers remained essentially the same, with India-Asia collision now reconstructed at ~52–58 Ma [e.g., *Najman et al.*, 2010; *DeCelles et al.*, 2014; *Garzanti and Hu*, 2014], plate convergence since 52 Ma being up to ~3600 km [*van Hinsbergen et al.*, 2011a], and estimated upper crustal shortening within Asia (600–750 km [*Yin and Harrison*, 2000; *Johnson*, 2002; *Guillot et al.*, 2003; *van Hinsbergen et al.*, 2011b]) and the Himalaya (up to 900 km [*DeCelles et al.*, 2002; *Long et al.*, 2011]) adding up to less than half of the contemporaneous convergence.

Explanations for this major mismatch fall into three categories. First, shortening in Asia may be drastically underestimated, for example, by extrusion of Indochina from an original position within Tibet, and/or by intra-Asian continental subduction [*Tapponnier et al.*, 2001; *Royden et al.*, 2008; *Replumaz et al.*, 2013]. Second, the collision age may be much younger; for example, collision at 34 Ma [*Aitchison et al.*, 2007], or 40 Ma [*Bouilhol et al.*, 2013], or 44 Ma [*Gibbons et al.*, 2015] may explain (part of) the misfit. Third, the size of Greater India at the time of collision may be much larger than traditionally assumed, such that wholesale subduction

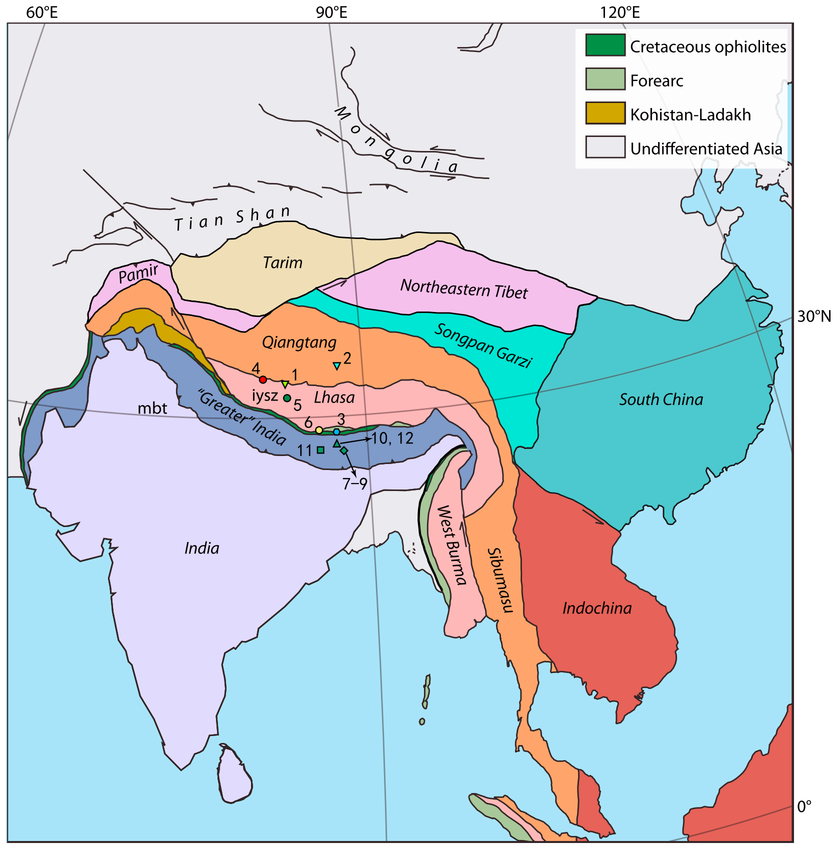

Figure 1. Tectonic map of the India-Asia collision zone (modified from *van Hinsbergen et al.* [2012]). IYSZ: Indus-Yarlung Suture Zone; MBT: Main boundary thrust. Symbols (triangle, hexagon, circle, and square) represent the reference positions of paleomagnetic data with sources (1–12) presented in Table 1.

of large volumes of Indian lithosphere would explain the mismatch between convergence and shortening estimates [*Patzelt et al.*, 1996; *Dupont-Nivet et al.*, 2010b, 2010a; *Yi et al.*, 2011]. For example, paleomagnetic data from the TH are consistent with as much as ~2000 km of intra-Greater India paleolatitudinal divergence during the Cretaceous, such that much of Greater India would have consisted of oceanic lithosphere separating a Tibetan Himalayan microcontinent from the Indian craton [*van Hinsbergen et al.*, 2012]. *Wang et al.* [2014], however, recently argued that this divergence does not represent N-S extension but instead merely results from ~90° counterclockwise rotation of the Indian plate in the Cretaceous; this argument implicitly assumes that Greater India had always been over 2000 km wide.

Importantly, the kinematic predictions for each of these proposals can be tested against paleomagnetic data. A recent proliferation of paleomagnetic data from southern Tibet and the Tibetan Himalaya has been carefully analyzed for paleomagnetic artifacts to ensure consistent data quality—e.g., sedimentary inclination shallowing, remagnetization, underrepresentation or overrepresentation of paleosecular variation, and variable data selection criteria [see, e.g., *Tan et al.*, 2010; *Lippert et al.*, 2014; *Huang et al.,* 2013, 2015a, 2015b, 2015c, 2015d]. Here we use these most robust paleomagnetic data to test the viability of the three end-member reconstructions summarized above. We indicate feasibilities and limitations of each scenario, define kinematic boundaries, and identify targets for future tectonic research in the collision zone.

2. Approach and Data Selection

To test the kinematic models of the India-Asia collision zone, we aim to compare model predictions for the paleolatitudes of the blocks involved in the collision zone to paleolatitudes determined from paleomagnetic data. Each tectonic scenario for the collision zone predicts a specific relative motion of a part of a crustal block that provided the data relative to Eurasia (for Tibet) and to India (for the Himalaya), which we implement in global plate reconstructions using Gplates software [*Boyden et al.*, 2011] with rotation parameters for the global plate circuit of *Torsvik et al.* [2012]. India and Asia are connected to this plate circuit in these reconstructions, which is then placed in a paleomagnetic reference frame based on the global apparent polar wander path (GAPWaP) of *Torsvik et al.* [2012]. Thus, the position of sampling localities is determined relative to the Earth's magnetic paleopole. We calculate the uncertainty for the predicted paleolatitude from the error reported for the GAPWaP. Then, we compare the predicted paleolatitude to the one calculated from the paleomagnetic data determined from these localities.

Selection of the paleomagnetic data followed the criteria and procedures described in *Lippert et al.* [2014], in which a robust paleomagnetic pole must be calculated from a large number of primary, well-determined geomagnetic field recordings, carefully assessing whether paleosecular variation is represented, compaction-induced inclination shallowing of sedimentary rocks has been corrected for, and remagnetization can be excluded or corrected for. The selected paleomagnetic results are provided in Table 1.

Tibetan paleolatitudes were obtained for the Qiangtang terrane using paleomagnetic data from upper Eocene to lower Oligocene (35 ± 3 Ma) lavas reported by *Lippert et al.* [2011]. For the Lhasa terrane, a late Eocene to early Oligocene (35 ± 5 Ma) paleolatitude was determined from red beds after correction for inclination shallowing [*Ding et al.*, 2014]. Early Eocene (~52 Ma) paleolatitudes were obtained from pristine lavas with no evidence for remagnetization [*Dupont-Nivet et al.*, 2010b; *Tan et al.*, 2010; *Lippert et al.*, 2014; *Huang et al.*, 2015c]. Notably, paleomagnetic results corrected for inclination shallowing from sedimentary rocks interbedded with and immediately above these lavas [*Huang et al.*, 2013], and inclinations derived from coeval lavas corrected for partial remagnetization [*Huang et al.*, 2015b] are indistinguishable from directions in the pristine lavas. Early Cretaceous (~125 Ma) paleolatitudes are determined from a large number of lava sites [*Chen et al.*, 2012; *Ma et al.*, 2014; *Yang et al.*, 2014] at two localities, and inclination shallowing-corrected sedimentary rocks from the oceanic Gangdese fore arc that bordered the Lhasa terrane to the south, along the subduction zone that consumed the Neotethys [*Huang et al.*, 2015a]. For the TH, robust paleomagnetic poles are available for the following time intervals: (1) 57 ± 2 Ma [*Yi et al.*, 2011], (2) 60 ± 2 Ma [*Yi et al.*, 2011], (3) 68 ± 3 Ma [*Patzelt et al.*, 1996], (4) 116 ± 5 Ma [*Klootwijk and Bingham*, 1980], (5) 134 ± 4 Ma [*Huang et al.*, 2015d], and (6) 227 ± 13 Ma [*Appel et al.*, 1991] (Table 1).

3. Analysis

3.1. Testing Intra-Asia Shortening Estimates

We first test paleolatitudes predicted by a recent kinematic reconstruction of Asia based on structural geologic data that estimated 600–750 km of shortening across and north of Tibet since 50 Ma [*van Hinsbergen et al.*, 2011b, and references therein]. This scenario is similar to earlier estimates of *Dewey et al.* [1988] and *Yin and Harrison* [2000] but is about twice as high as *Yakovlev and Clark* [2014], and at least ~1000 km smaller than scenarios advocating major Indochina extrusion [e.g., *Replumaz and Tapponnier*, 2003; *Royden et al.*, 2008].

The paleolatitudes for the Lhasa and Qiangtang paleomagnetic localities at ~35 Ma are lower than those predicted by the reconstruction, with error bars barely overlapping (Figure 2a). The paleolatitude predicted for the lower Eocene (52 Ma) lavas only overlaps with the northernmost values of the measured paleolatitudinal range (Figure 2b). The kinematic reconstruction of Asia at 125 Ma includes an additional ~400 km of Cretaceous shortening estimated from the Lhasa and Qiangtang terranes [e.g., *Kapp et al.*, 2005; *van Hinsbergen et al.*, 2011b] (Figure 2c). The predicted paleolatitudes at all three reference positions are well within the range of the measured paleolatitudes. Thus, the paleomagnetic data indicate that the shortening reconstructions predict latitudes consistent with paleomagnetic data representing ~125 Ma, only just within error at 52 Ma, and up to ~300 km north at 35 Ma.

The 35 Ma mismatch may result from the widely debated "Asian inclination anomaly," which might be caused by nondipolar geomagnetic field behavior [*Dupont-Nivet et al.*, 2010a] or major tectonic motions of Asia relative to North America and Europe along undocumented Cenozoic fault zones [e.g., *Cogné et al.*, 2013] but may alternatively indicate that the estimated 600–750 km Cenozoic intra-Asian shortening [*van Hinsbergen et al.*, 2011b] should be considered a minimum value. Assuming a higher total intra-Asian post 50 Ma shortening value of ~900 km, with the excess ~300 km accumulated after 35 Ma, would bring all predicted paleolatitudes within the observed range. How and where this excess shortening was accommodated,

Table 1. Observed Paleomagnetic Data for the Qiangtang and Lhasa Terranes and Tibetan Himalaya[a]

			Reference Position			Pole											
Location	Stratigraphic Age	Age (Ma)	Latitude (°N)	Longitude (°E)	N (*N*, *n*)	Latitude (°N)	Longitude (°E)	A95 (deg)	Dec (deg)	ΔDec (deg)	Inc (deg)	ΔInc (deg)	λ_p (deg)	$\Delta\lambda_l$ (deg)	$\Delta\lambda_u$ (deg)	Source
						Qiangtang and Lhasa Terranes										
Southern Qiangtang	Eocene-Oligocene	35 ± 3	33	88	20	-	-	-	-	-	-	-	28.7	3.7	3.7	1
Gerze	Eocene-Oligocene	35 ± 5	32.2	84.3	35	71.7	339.3	3.1	340.3	3.4	44.2	3.9	25.9	3	3.2	2
Penbo	Ypresian	52 ± 4	29	88	52	80.1	248.6	3.9	3.5	4.1	35.5	5.8	19.6	3.7	4.1	3
Yahu	Lower Cretaceous	126 ± 6	32.3	82.8	51	61.4	192.9	2.1	28.4	2.2	35	3.2	19.3	2	2.2	4
Deqing and Cuoqin	Lower Cretaceous	120 ± 10	31.2	84.5	30	64.9	328	5.5	336.5	5.8	32.8	8.6	17.9	5.2	5.9	5
Sangsang	Lower Cretaceous	~129 (MDA)	29.3	86.6	117	-	-	-	351	3.6	30.2	-	16.8	5.7	6.5	6
						Tibetan Himalaya										
Upper Zongpu	Thanetian	57 ± 2	28.3	88.5	14.0	71.6	277.8	2.5	357.0	2.5	19.6	4.6	10.1	2.5	2.6	7
Lower Zongpu	Selandian	60 ± 2	28.3	88.5	18.0	67.3	266.3	3.5	0.9	3.5	11.1	6.8	5.6	3.5	3.6	8
Zongshan	Campanian–Maastrichtian	68 ± 3	28.3	88.5	144.0	55.8	261.6	3.5	3.9	3.5	−11.4	6.8	−5.8	3.6	3.5	9
Thakkhola–Dzong Fm	Aptian	116 ± 5	29.0	88.0	95.0	12.0	288.7	3.7	331.1	5.2	−63.0	3.0	−44.5	3.8	3.6	10
Wölong Fm	Lower Cretaceous	134 ± 4	28.5	87.0	201.0	4.4	−104.0	3.0	19.7	5.3	−71.1	2.0	−55.6	3.1	2.9	11
Manang	Anisian to lower Norian	227 ± 13	29.0	88.0	40.0	22.2	286.8	4.9	338.4	6.0	−55.3	4.8	−35.8	5.2	4.6	12

[a]Location: region from which paleomagnetic data were collected. Stratigraphic ages follow *Garzanti* [1999] and corresponding absolute ages follow *Gradstein et al.* [1994] unless section is dated using radiometric techniques. N (*N*, *n*): the number of paleomagnetic poles (VGPs, samples) used to define the mean paleomagnetic poles listed in this table. A95: the radius of the 95% confidence cone on the mean pole; when calculated from samples rather than poles of VGPs, $A95 = (dp \times dm)^{0.5}$, calculations follow *Butler* [1992]. MDA: maximum depositional age. Dec ± ΔDec, Inc ± ΔInc, $\lambda_p \pm \Delta\lambda_p$: declination, inclination, paleolatitude with 95% confidence interval for a reference site from pole; calculations follow *Butler* [1992]. Sources: 1: *Lippert et al.* [2011]; 2: *Ding et al.* [2014]; 3: *van Hinsbergen et al.* [2012], *Lippert et al.* [2014], and *Huang et al.* [2013, 2015b, 2015c]; 4: *Ma et al.* [2014]; 5: *Chen et al.* [2012] and *Yang et al.* [2014]; 6: *Huang et al.* [2015a]; 7 and 8: *Yi et al.* [2011]; 9: *Patzelt et al.* [1996] and *Dupont-Nivet et al.* [2010a, 2010b]; 10: *Klootwijk and Bingham* [1980]; 11: *Huang et al.* [2015d]; 12: *Appel et al.* [1991].

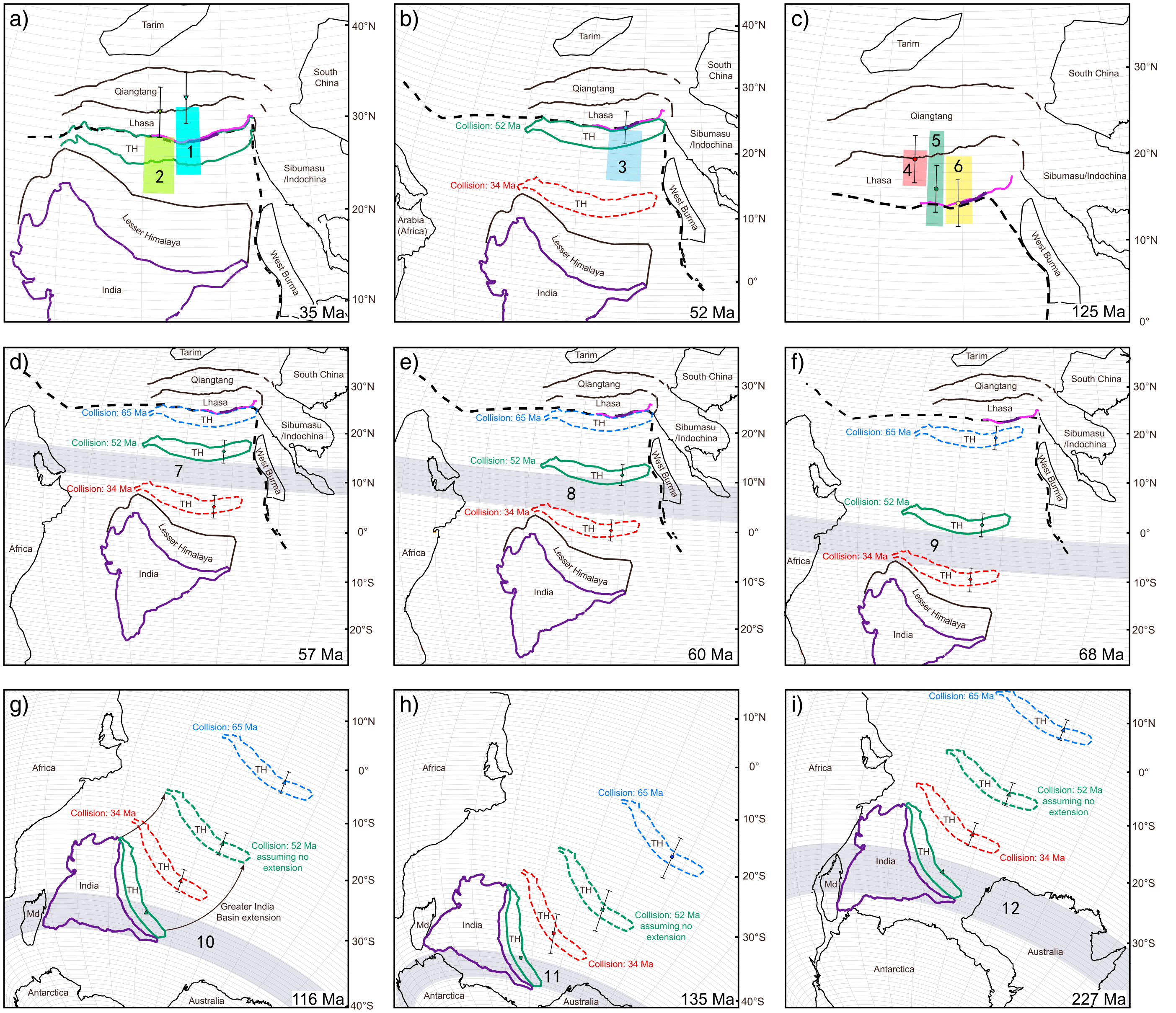

Figure 2. Paleomagnetic tests of tectonic reconstructions. Kinematic reconstructions of Asia are based on ~600–750 km of postcollisional intra-Asian shortening and ~400 km of precollisional shortening within the Lhasa and Qiangtang terranes [*Kapp et al.*, 2005; *van Hinsbergen et al.*, 2011b]. The shaded areas are the measured paleolatitudinal ranges with data sources (1–12, same as in Figure 1) displayed in Table 1. Uncertainties of the predicted paleolatitudes are determined from the error reported for the GAPWaP. TH: Tibetan Himalaya; pink thick lines: Yarlung Zangpo ophiolites; dashed thick lines: subduction zone in the Neotethys. (a) Predicted paleolatitudes of the Qiangtang and Lhasa terranes compared to the observed paleolatitudes at ~35 Ma; (b, c) predicted paleolatitudes of the Lhasa terrane compared to the observed paleolatitudes at ~52 Ma and ~125 Ma, respectively; (d–f) kinematic reconstructions showing the predicted positions of the TH depending on the assumed collision ages at 34, 52, and 65 Ma for comparison with the observed paleolatitudes at ~57 Ma, ~60 Ma, and ~68 Ma. The measured paleolatitudes of the TH are consistently 1–2° south of the lower bound of predicted values. (g–i) Kinematic reconstructions of the TH at ~116 Ma, ~135 Ma, and ~227 Ma. Regardless of collision age, the predicted paleolatitudes of the TH (dashed lines) are significantly north of the upper limit of the measured paleolatitudes assuming no extension has happened within Greater India during the Cretaceous. Placing the TH (solid lines) adjacent to the northern margin of India will make the predicted paleolatitudes consistent with the measured values.

however, remains to be identified in future work. Over 900 km of postcollisional intra-Asian shortening would lead to predicted paleolatitudes at 125 Ma that are lower than those observed in the paleomagnetic data. Kinematic reconstructions of Asia that assume 2000 km of Cenozoic shortening [*Tapponnier et al.*, 2001; *Replumaz and Tapponnier*, 2003; *Royden et al.*, 2008] predict paleolatitudes of the Lhasa terrane far south of the measured ones.

3.2. Testing Collision Ages

With the magnitude of India-Asia convergence determined by the plate circuit, and the amount of intra-Asian shortening estimated, the age of collision thus predicts the amount of Indian plate subduction after collision (i.e., predicts the size of Greater India). We use the intra-Asia shortening reconstruction of *van Hinsbergen et al.* [2011b], bearing in mind a potential underestimate up to 300 km after 35 Ma. We then test the viability of proposed collision ages by comparing the paleolatitude predicted by the GAPWaP with data from the TH, assuming the TH was part of Greater India before collision.

Assuming a collision age of 52 Ma, which is considered a minimum collision age according to stratigraphic and sedimentologic data [*Najman et al.*, 2010; *Hu et al.*, 2012], the measured paleolatitudes of the TH are consistently 1–2°S of the lower bound of predicted values at 57 Ma, 60 Ma, and 68 Ma (Figures 2d–2f). Considering the fast northward motion rates of the Indian plate in this time interval (>1°/Myr in a paleomagnetic reference frame), this may indicate either that collision occurred 1–2 Ma later or that there is ~200 km of additional intra-Asian shortening. This latter option is supported by the growing stratigraphic, sedimentologic [*DeCelles et al.*, 2014; *Garzanti and Hu*, 2014], and metamorphic [*Guillot et al.*, 2008] evidences for a collision age no younger than 52 Ma.

Collision ages of 34 Ma [*Aitchison et al.*, 2007] or 65 Ma [*Klootwijk et al.*, 1992; *Ding et al.*, 2005] result in predicted paleolatitudes of the TH that are either far south or far north of the ranges of the measured paleolatitudes at 57 Ma, 60 Ma, and 68 Ma (Figures 2d–2f), respectively. Tibetan sites at latitudes that are consistent with paleomagnetic data would require an amount of intra-Asian shortening that is precluded by the paleomagnetic data of the Lhasa terrane.

Recently, new sedimentologic data were used to advocate collision ages of 56–58 Ma [*DeCelles et al.*, 2014; *Garzanti and Hu*, 2014; *Orme et al.*, 2014]. This scenario requires ~600–900 km more postcollisional shortening within Asia than the estimates suggested by *van Hinsbergen et al.* [2011b] (Figures 2d–2f). At 35 Ma and 52 Ma, such excess shortening is paleomagnetically permitted, although its location or distribution is unknown. However, such postcollisional shortening predicts paleolatitudes that are far too south positioned from those documented at 125 Ma (Figure 2c). Even when assuming that no precollisional shortening occurred, 125 Ma Tibetan paleolatitudes preclude a collision age older than ~55 Ma.

3.3. Testing "Greater Indian Basin" Extension

Finally, we consider Late Triassic to Early Cretaceous paleolatitudes for the TH. For a Greater India constrained by collision at 52 Ma and following the intra-Asian shortening estimates of *van Hinsbergen et al.* [2011b], the predicted paleolatitudes of the TH are 12–16°N of the upper limit of the measured paleolatitudes at 116 Ma, 135 Ma, and 227 Ma (Figures 2g–2i). This result requires that the TH must have separated and drifted northward relative to India, as part of a separate plate, between 116 Ma and 68 Ma. Importantly, these Triassic and Cretaceous reconstructions take into account counterclockwise rotation of ~90° of India relative to Asia, which thus clearly cannot explain the paleolatitudinal separation of the TH relative to India, as proposed by *Wang et al.* [2014]. If we assume collision ages of 34 Ma and 65 Ma, then the predicted paleolatitudes of the TH are also significantly north of the measured values for the Early Cretaceous and Late Triassic (Figures 2g–2i). Therefore, regardless of the collisional scenario, extension within Greater India is always required to explain the observed paleolatitudes.

A single latitudinal adjustment of the TH, placing it adjacent to the northern margin of India corrected for Lesser Himalayan shortening [*Long et al.*, 2011] at 116 Ma, and assuming the TH was fixed to India before that time is sufficient to make predicted paleolatitudes of the TH consistent with the measured paleolatitudinal ranges at 116 Ma, 135 Ma, and 227 Ma (Figures 2g–2i). This requires an Early Cretaceous paleogeography with a small Greater India (<1000 km), consistent with stratigraphic data and Gondwana fits for Greater India [e.g., *Garzanti*, 1999; *Ali and Aitchison*, 2005; *Gibbons et al.*, 2012; *McQuarrie et al.*, 2013].

4. Conclusions

We use paleomagnetic data to test tectonic reconstructions of the India-Asia collision zone and provide permissible ranges of intra-Asian convergence, intra-Indian divergence, and collision ages. We predict paleolatitudes by placing kinematic reconstructions of the collision zone in a global plate reconstruction that is constrained relative to the Earth's magnetic field using the global apparent wander path. We conclude that paleolatitude data from Indian units of Triassic to present age are sensitive to testing the paleogeography of Greater India. We also suggest that a recent kinematic reconstruction that estimates 600–750 km of intra-Asia postcollisional shortening is a minimum value and that a value of 900 km is more consistent with the paleomagnetic data, with the excess shortening accommodated after 35 Ma. An additional 400 km of geologically estimated Cretaceous shortening within the Lhasa and Qiangtang terranes is also permitted by paleomagnetic data. If we assume the maximum amount of intra-Asia convergence that is consistent with the paleomagnetic constraints, then collision could have been underway by 52 Ma. Kinematic reconstructions based on younger (34 Ma) or older (65 Ma) collision ages are inconsistent with paleomagnetic results. Also, we find that recently proposed collision ages of 56–58 Ma are not compatible with the paleomagnetic constraint: even if we assume no precollisional intra-Asian convergence, Tibetan paleolatitudes at 125 Ma preclude a pre-55 Ma collision. Furthermore, paleomagnetic data from the Lower Cretaceous and Upper Triassic Tibetan Himalayan strata unequivocally require substantial extension between the TH and India between 116 and 68 Ma for any proposed India-Asia collision age ranging from 34 to 65 Ma; the magnitude of the paleolatitudinal discrepancy cannot be explained by the counterclockwise rotation of India with respect to Asia. Collision at 52 Ma would require at least 15° paleolatitudinal divergence within Greater India, resulting in 2000 km of reconstructed extension during the Cretaceous.

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