GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G52634.1

Manuscript received 28 July 2024
Revised manuscript received 8 December 2024
Manuscript accepted 24 January 2025

Published online 7 February 2025

An asymmetric Late Cretaceous back-arc basin south of Tibet?

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ABSTRACT

The Indus-Yarlung suture zone (southern Tibet) between the Indian plate–derived Tibetan Himalaya and the Asian continental crust intruded by the Gangdese magmatic arc of southern Tibet hosts a <20-km-wide band of ophiolites overlain by Asia-derived clastic sedimentary rocks of the Xigaze forearc basin. How wide this basin was prior to India-Asia collision is unknown: it may have been a typical forearc basin width, i.e., ~150–200 km, but was also proposed to have become separated from Tibet in the Late Cretaceous by a back-arc basin thousands of kilometers wide. To test this, we present the first paleomagnetic study of upper Cretaceous redbeds of the 71.2–69.3 Ma Padana Formation in the Xigaze forearc basin, near Sangsang town, Ngamring county, Tibet, China (~86°E). High-temperature magnetic components were isolated at 580 °C or 600–680 °C and passed reversal and fold tests demonstrating a primary magnetization that we corrected for inclination shallowing. Our results reveal that the Xigaze forearc basin at ~86°E was situated at 18.4° ± 3.6°N at ca. 70 Ma, indicating a separation from Lhasa of <500 km. To reconcile our new data with coeval, much lower, paleolatitudes from the Ladakh arc to the west (~77°E) we reconstruct a Late Cretaceous–Paleogene opening and closure of an asymmetric back-arc basin in the western Neotethys. This suggests that the distribution of India-Asia convergence was laterally unevenly partitioned over the pre-collisional plate boundaries.

INTRODUCTION

The current understanding of the driving mechanisms of India-Asia convergence, the timing of collision, and the subsequent evolution of the Tibetan-Himalayan orogen critically depends on the reconstruction of pre-collisional subduction systems. The northward movement of India toward Eurasia may have been accommodated at a single subduction zone along the southern edge of the Eurasian plate (e.g., Royden et al., 2008; Ingalls et al., 2016; van Hinsbergen et al., 2019). However, convergence may also have been partitioned over additional intra-oceanic subduction systems (Tapponnier et al., 1981; Aitchison et al., 2007), which could significantly change our understanding of the geodynamic drivers of Indian plate motion (Jagoutz et al., 2015). Currently, both reconstruction views explain key observations, but are also challenged by data.

The arguments for and against multiple subduction zones hinge on data and interpretations from Lower Cretaceous supra-subduction zone ophiolites, associated metamorphic and sedimentary rocks that are preserved in a suture zone between Indian plate–derived continental rocks of the Himalaya, and Asian continental rocks in southern Tibet that are intruded by the Gangdese magmatic arc (Fig. 1). Paleomagnetic data from the Lower Cretaceous and lower Eocene in the Xigaze forearc basin show paleolatitudes of ~16–20°N (Meng et al., 2012; Huang et al., 2015; Li et al., 2022), immediately adjacent to southern Tibet (van Hinsbergen et al., 2019; Martin et al., 2023). This could be explained by a narrow oceanic forearc that formed between the Tibetan continental magmatic arc and a single southern Eurasian subduction zone (e.g., Maffione et al., 2015). However, westward, the suture zone widens and contains the intra-oceanic Kohistan-Ladakh arc, bounded by the Indus suture to the south and the Shyok suture to the north, between the Lower Cretaceous ophiolite belt and continental Asia (Rolland et al., 2000; Hébert et al., 2012; Bouilhol et al., 2013; Jagoutz et al., 2015). Provenance analysis reveals that sedimentary rocks in the Ladakh arc ca. 90 Ma were derived from Tibet (Borneman et al., 2015), suggesting that the Kohistan-Ladakh subduction record may originally have formed adjacent to Tibet. However, a paleomagnetic pole from 18 sites in ca. 66 Ma volcanic flow units of the Ladakh arc shows a paleolatitude of 8.1° ± 5.6°N, far south of Tibet (Martin et al., 2020). Moreover, geochemical and geochronological data from plutonic rocks of the Kohistan-Ladakh batholith suggest that a subduction zone (currently the Shyok suture) may have existed north of Kohistan-Ladakh until the Eocene (Bouilhol et al., 2013), supporting the simultaneous Late Cretaceous to Eocene activity of two subduction systems. Seismic tomographic analyses of subducted slabs have provided arguments for and against dual subduction systems (e.g., Parsons et al., 2020; Qayyum et al., 2022).

Kapp and DeCelles (2019) offered a possible reconciliation by invoking the Late Cretaceous opening of a back-arc basin separating a plate from the Eurasian plate that contained the Xigaze forearc and Kohistan-Ladakh arcs and bringing them toward the equator in the latest Cretaceous. This would be followed by back-arc basin closure along the Shyok suture and structures coinciding with, or buried by, the Gangdese thrust (e.g., Laskowski et al., 2018). The straightforward quantitative way to test this hypothesis is through the collection of paleomagnetic data from the Upper Cretaceous of the Xigaze forearc basin.

We report paleomagnetic results from the upper Padana Formation in the Xigaze forearc basin near Sangsang, at ~86°E (Fig. 1), which accumulated at ca. 70 Ma; i.e., only slightly older than the ca. 66 Ma Ladakh paleomagnetic pole of Martin et al. (2020). We use our results to investigate the paleopositions of the Xigaze forearc at the critical ca. 70 Ma time slice and evaluate how Xigaze and Kohistan-Ladakh records may be reconciled into a plate kinematic scenario.

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CITATION: Xu, S., et al., 2025, An asymmetric Late Cretaceous back-arc basin south of Tibet?: Geology, v. 53, p. 392–397, https://doi.org/10.1130/G52634.1

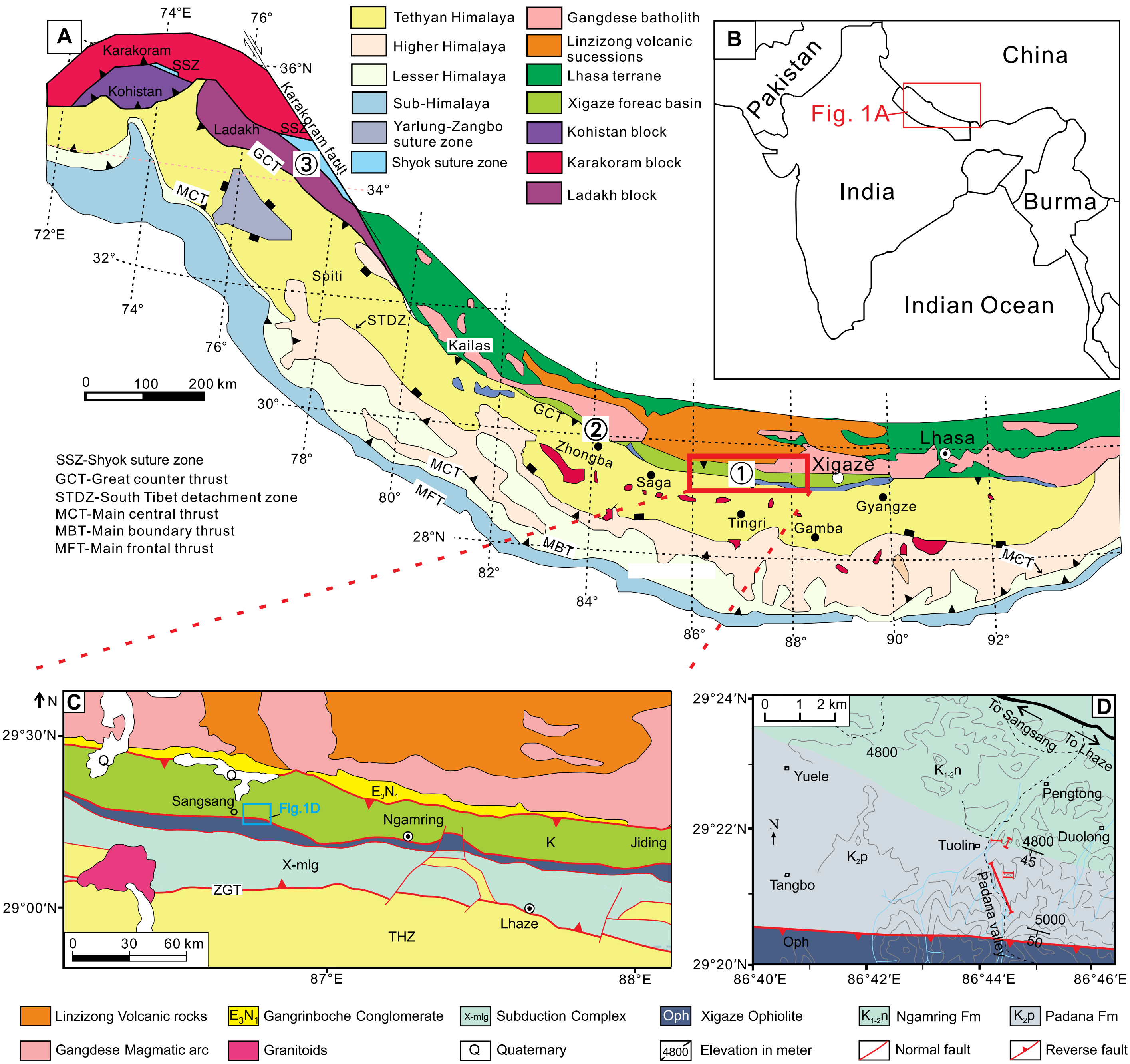

Figure 1. Geological map of the study area in the Xigaze forearc basin, Tibet. (A, B) Simplified geological map of the Himalaya (after An et al., 2014; Parsons et al., 2020). 1—Sangsang section (this study); 2—Cuojiangding section (Meng et al., 2012; Li et al., 2022); 3—Kohistan-Ladakh (Martin et al., 2020). (C) Geological sketch of the study area and surrounding units (after An et al., 2014). K—Cretaceous strata; ZGT—Zhongba-Gyangze thrust; THZ—Tethyan Himalayan zone. (D) The Sangsang section consists of subsection I and subsection II.

SETTING, SAMPLING, AND METHODS

The Xigaze forearc basin consists of Lower Cretaceous (ca. 130 Ma) to Lower Eocene marine and terrestrial clastic sedimentary rocks (An et al., 2014; Huang et al., 2015; Orme et al., 2015). These overlie Lower Cretaceous forearc ophiolites, either unconformably onto mantle rocks that exhumed to the forearc sea floor, or interfingering with radiolarites that cover pillow lavas (Huang et al., 2015; Maffione et al., 2015). The key stratigraphic interval for our study is the shallow marine Padana Formation, which is Late Cretaceous in age (An et al., 2014; see Appendix S1-1 in the Supplemental Material[1]). We sampled these in two sections (subsection I and subsection II) close to Sangsang town (Fig. 1), stratigraphically above the Lower Cretaceous Sangsang section sampled by Huang et al. (2015) that yielded a paleolatitude of ∼16° ± 4°N at 128.8 Ma ± 3.4 Ma. We collected 167 standard paleomagnetic cores from the Padana Formation using a portable gasoline-powered rock drill and oriented by a magnetic compass. In addition, 7 oriented blocks were collected from which another 19 core samples were drilled in the laboratory. Laboratory treatments and data analyses follow the standard paleomagnetic protocols (see Appendix S1-2 in the Supplemental Material).

[1]Supplemental Material. Appendix S1, Figures S1–S5, and Table S1. Please visit https://doi.org/10.1130/GEOL.S.28324154 to access the supplemental material; contact editing@geosociety.org with any questions.

RESULTS

Progressive thermal demagnetization of 263 paleomagnetic specimens indicates that most specimens generally show two-component magnetizations (Fig. 2B), with components of linear fit of temperature steps above 500 °C regarded as the characteristic remanent magnetization (ChRM) (see Appendix S1-3 in the Supplemental Material). The interpreted ChRMs contain both normal and reversed directions that pass a reversal test, and directions sampled in two limbs of a fold pass a fold test (see Appendix S1-4 in the Supplemental Material), and the 95% confidence angle around the pole position (A_{95}) of 3.4° falls within the n-dependent reliability envelope of Deenen et al. (2011) (A_{95min}, A_{95max} = 1.7°, 3.8°, respectively) suggesting that the scatter is straightforwardly explained by paleosecular variations. We therefore interpret the ChRM as the primary remanence and obtained paleomagnetic directions from 132 specimens. Our paleomagnetic results pass the criteria of Vaes et al. (2021) for using the elongation/inclination (E/I) technique (Tauxe and

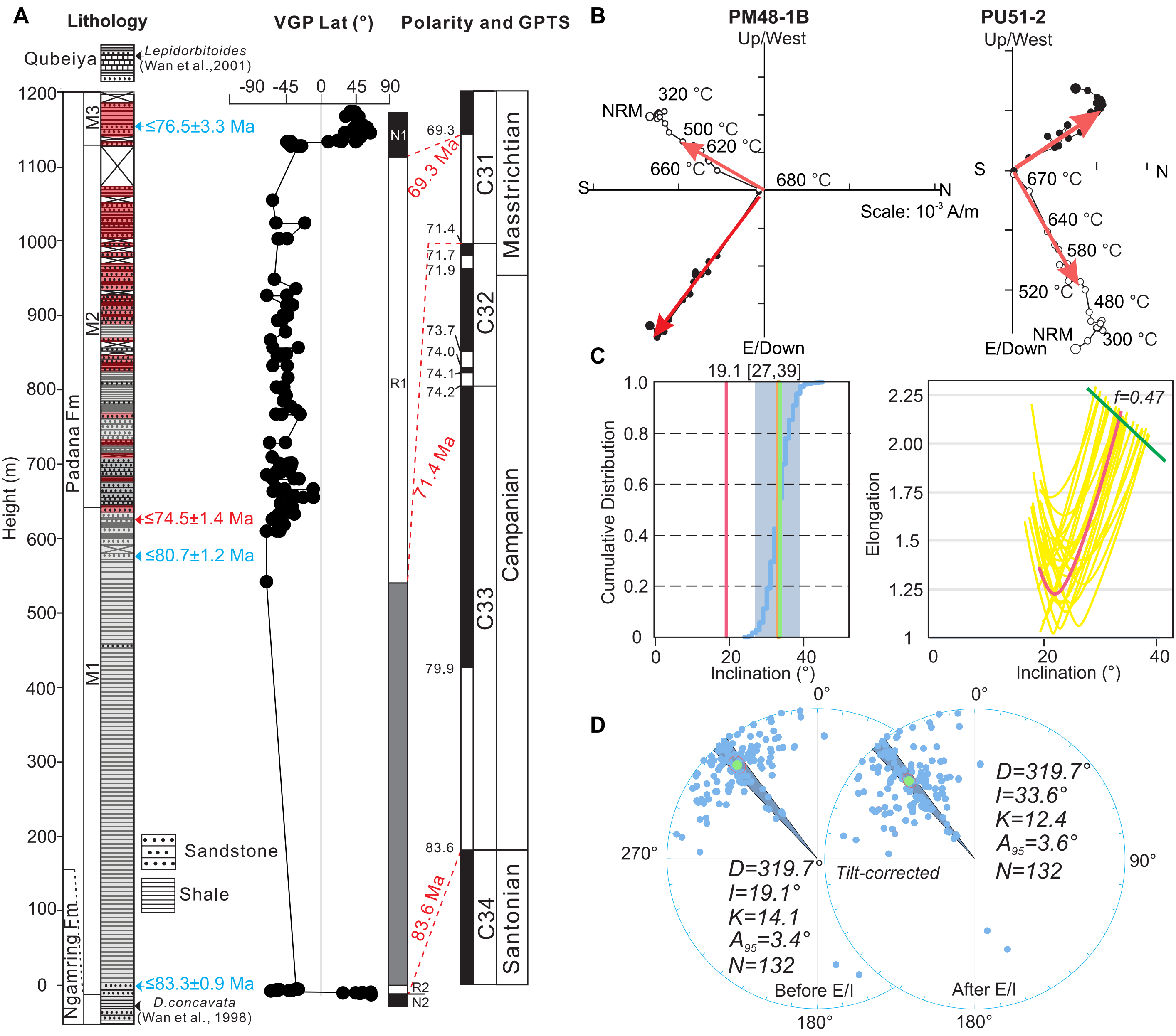

Figure 2. Magnetostratigraphic and paleomagnetic results from the Padana Formation in the Xigaze forearc basin, Tibet. (A) Integrated bio-, litho-, and magneto-stratigraphic results from the Sangsang section (location shown in Fig. 1). Black/white zones represent normal/reversed polarity intervals, and the gray zone indicates the undetermined polarity. GPTS is the Geomagnetic Polarity Time Scale 2020 (Ogg, 2020). VGP—virtual geomagnetic pole. Ages in blue are the detrital zircon U-Pb ages (YC1σ[2+]) from the Sangsang section (An et al., 2014) and the age in red is detrital zircon U-Pb age (YC1σ[2+]) of the comparable strata from the Cuojiangding section (Hu et al., 2016) (see Appendix S1-5 in the Supplemental Material [see text footnote 1]). Qubeiya—Qubeiya Formation; *D. concavata—Dicarinella concavata* foraminifera zone. (B) Demagnetization data in stratigraphic coordinates of representative specimens from Padana Formation. Solid (open) symbols represent projections onto the horizontal (vertical) planes, with red arrows marking high-temperature magnetic components. NRM—natural remanent magnetization. (C) Elongation/inclination (E/I) correction (Tauxe and Kent, 2004) applied to the characteristic remanent magnetizations (ChRMs). Red line represents observed mean inclination; green line indicates the unflattened mean inclination (*f*—flattening factor). The bar marks the confidence interval of the unflattened inclinations. The yellow line denotes the average bootstrapped inclination using the E/I technique. (D) ChRM distributions before and after the E/I correction. Blue dots denote ChRMs and green dots indicate the means of ChRMs. A_{95}—95% confidence angle around the pole position.

Kent, 2004) to correct for inclination shallowing, yielding a flattening factor, *f*, of 0.47 (see Appendix S1-6 in the Supplemental Material). The E/I-corrected paleomagnetic data yield a mean of declination $D_s = 319.7° \pm 3.8°$, inclination $I_s = 33.6° \pm 5.6°$, Fisher precision parameter $K = 12.4$, $A_{95} = 3.6°$, N = 132 in stratigraphic coordinates (Fig. 2D), corresponding to a paleolatitude of 18.4 ± 3.6° N for the Xigaze forearc.

Variations in virtual geomagnetic pole (VGP) latitude with the stratigraphic level are shown in Figure 2. Four magnetozones include two normal and two reversal polarity zones (Fig. 2). The magnetic polarity for the 7.9–553.5 m interval cannot be determined because these shales were not suitable for sampling (Fig. 2). The uppermost of the Padana Formation in the Sangsang section yielded a maximum depositional age of 76.5 ± 3.3 Ma (Fig. 2; An et al., 2014), which falls within a normal polarity-dominated part of the time scale with reversed intervals of only ~0.2 m.y. (Chron C32). Correlating our section to these short intervals would yield unrealistically high sedimentation rates (>200 cm/k.y.), and we thus correlate the reversed magnetozone to the longer interval, C31r interval boundaries; i.e., 71.4–69.3 Ma (see Appendix S1-5 in the Supplemental Material; Fig. 2; Ogg, 2020).

DISCUSSION

The paleolatitude predicted by tectonic reconstructions of Tibetan crustal shortening at the location of Sangsang based on structural geological data and paleolatitude data of the Lhasa terrane (van Hinsbergen et al., 2019), when placed in a paleomagnetic reference frame (Vaes et al., 2023), is ~22°N. Our data revealing 18.4° ± 3.6°N thus shows that the separation of the Xigaze forearc at 86°E at ca. 70 Ma may have been negligible and did not exceed ~5°, or ~500 km. This is in line with previous conclusions from paleomagnetic data of the Lower Cretaceous (Huang et al., 2015), Maastrichtian (Li et al., 2022), and Eocene (Meng et al. 2012; Li et al., 2022) that all show a paleomagnetically insignificant separation between the Xigaze forearc and the southern Lhasa margin. Such a limited separation clearly explains the detrital zircon populations in the Padana Formation that were interpreted to derive from the Gangdese magmatic arc and the Lhasa terrane (An et al., 2014). These data demonstrate that at the longitude of Sangsang, no ~2000-km-wide back-arc basin existed during Late Cretaceous time between the Lhasa terrane and the Xigaze forearc basin, and the Xigaze forearc basin was not part of an equatorial subduction system as proposed by, e.g., Aitchison et al. (2007), Jagoutz et al. (2015), Westerweel et al. (2019), and Kapp and DeCelles (2019). This argues against a near-equatorial, east-west–trending intra-oceanic subduction system that was proposed to connect the Kohistan-Ladakh arc to an arc record found on the West Burma block in Myanmar, which was also located near the equator in Late Cretaceous time (Westerweel et al., 2019). This record of the West Burma block may instead be explained as associated with plates that carried remains of Argoland from Gondwana to Eurasia in the eastern Neotethys, east of the Indian plate (Advokaat and van Hinsbergen, 2024).

Our results from Sangsang are consistent with a scenario of a single subduction zone along southern Tibet from the Early Cretaceous to the Paleocene collision that made the Tibetan Himalaya fold-thrust belt. However, the Ladakh (and Kohistan) arcs are also located north of the Early Cretaceous ophiolites that underlie the Xigaze forearc basin (e.g., Hébert et al., 2012), and the paleomagnetic data from the Ladakh arc (~77°E) at ca. 66 Ma reveal a paleolatitude that is much farther south (~8.1° ± 5.6°N; Martin et al., 2020) than our ca. 70 Ma data from Sangsang at ~86°E. Moreover, the Kohistan-Ladakh arcs are separated from the Tibetan terranes by a well-defined suture zone, the Shyok suture (Fig. 1), which thus requires that considerable convergence has occurred between the Kohistan-Ladakh arcs and Tibet. The concept of Late Cretaceous back-arc basin opening proposed by Kapp and DeCelles (2019) may offer a way to reconcile these data but with the modification that back-arc basin opening and subsequent closure was no more than ~500 km at ~86°E and increased westward toward Ladakh and Kohistan (Fig. 3).

We provide a tentative, hypothetical reconstruction of the South Tibetan subduction system in which westward increasing, southward roll-back opens a triangular back-arc basin that separated the Kohistan-Ladakh arc from a subduction zone that initially formed close to the south-Tibetan margin (Fig. 3). This follows earlier suggestions of Rolland et al. (2000) but with much larger extension, and is in line with arguments of Kapp and DeCelles (2019) that back-arc basin opening could start around this time based on a lull in Gangdese magmatism, and satisfies the observation that ca. 90 Ma clastic sedimentary rocks in the Ladakh arc were Asia-derived (Borneman et al., 2015). In this scenario, the Kohistan-Ladakh arc was the westward intra-oceanic continuation of the continental Gangdese arc until the Late Cretaceous—a situation that may be analogous to the transition

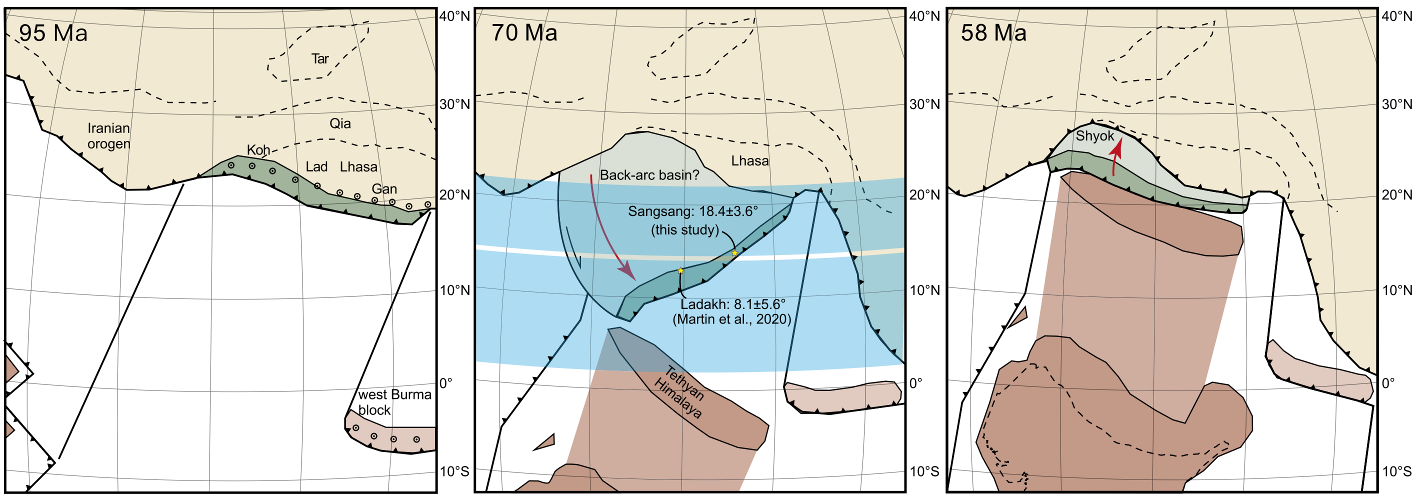

Figure 3. Paleogeographic maps showing the possible asymmetric back-arc basin that widens westward to explain the Late Cretaceous paleolatitudes for the Sangsang region in the Xigaze forearc basin, Tibet (this study), and the Ladakh arc (Martin et al., 2020). Open circles represent the locations of the volcanic arcs; yellow circles mark the paleopositions of Sangsang and Ladakh at ca. 70 Ma, with errors indicated by the blue shaded areas. Green shading denotes the refitted Xigaze-Ladakh forearc during 90–70 Ma. Reconstruction of India and Tibet follows van Hinsbergen et al. (2019) and of the west Burma block follows Advokaat and van Hinsbergen (2024). Reconstruction is cast in the paleomagnetic reference frame of Vaes et al. (2023). Tar—Tarim block; Qia—Qiadam block; Koh—Kohistan arc; Lad—Ladakh arc; Gan—Gangdese arc.

from the south Alaskan to the Aleutian arc today. This scenario is paleomagnetically permissible within the uncertainty bounds of the paleolatitudes at 70 Ma, at the lowest permitted latitude of our Sangsang section and the highest of the Ladakh section of Martin et al. (2020). If separations were larger than those modeled in our study (Fig. 3), then transform faults must have existed that separated the trench into segments with enhanced opening and closure rates toward the west.

Sometime in the latest Cretaceous, the hypothetical back-arc basin must have started closing, and closure must have been in its late stages by the time of arrival of the Tibetan Himalaya in the trench in the late Paleocene or early Eocene (Orme et al., 2015; An et al., 2021). Subsequently, ~25% of India-Asia convergence was partitioned over ongoing shortening in Tibet—which in the west may have been concentrated on the Shyok suture into the middle Eocene to explain ongoing volcanism there (Bouilhol et al., 2013)—and ~75% must have occurred to the south of the Tibetan and Greater Himalaya, consuming Indian plate lithosphere (Ingalls et al., 2016; van Hinsbergen et al., 2019; van Hinsbergen, 2022).

The hypothesized asymmetric back-arc basin resembles the modern geodynamic setting of the Lau Basin at the Tonga Trench (Schellart et al., 2006) and is well explained in geodynamic models of slab roll-back (Schellart et al., 2007). Those models show that toroidal flow of sub-slab mantle increases the propensity of slabs to roll back toward slab edges. Plate tectonic reconstructions and seismic tomographic analyses have shown that a long-lived transform plate boundary existed between the Indian and Africa-Arabian plates (e.g., Replumaz et al., 2004; van Hinsbergen et al., 2019; Parsons et al., 2020; Qayyum et al., 2022). The Kohistan-Ladakh region was thus close to a slab edge, whereas eastward, a contiguous Late Cretaceous subduction system existed that extended toward SE Asia.

The opening and closure of a westward-widening back-arc basin in the Neotethys Ocean south of Tibet may offer ways to reconcile sedimentological, paleomagnetic, and volcanic data of the youngest suture zone(s) north of the Himalaya. Nonetheless, the inferred kinematics of an asymmetric Late Cretaceous back-arc basin south of Tibet are currently based on a small number of paleomagnetic studies. In addition, our section reveals a net counterclockwise rotation, which is opposite from the reconstructed rotation of the forearc (Fig. 3C) and must thus result from local tectonic deformation in the suture zone (e.g., Laskowski et al., 2018). Testing such inferences requires an integrated structural-paleomagnetic analysis with regional coverage throughout the Xigaze forearc and its western continuations into the Ladakh and Kohistan arcs and Shyok suture. The results of such studies may require further modification of the plate kinematic history and plate boundary evolution in the times leading up to the India-Asia collision and may carry important constraints on understanding the geodynamic drivers of India's rapid plate motions.

ACKNOWLEDGMENTS

We thank Mark Dekkers for the discussion about the rock magnetic results, editor Tracy Rushmer, and reviewers Craig Martin, Devon Orme, and Yann Rolland for their constructive comments. This study was supported by the National Natural Science Foundation of China (grants 42488201 and 42174079) and the China Scholarship Council (grant 202206190078).

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Printed in the USA