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Subduction transference drove the Mesozoic convergence of microcontinents from Gondwana to Asia

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How microcontinents successively migrated from Gondwana to Eurasia is paramount in understanding the Mesozoic evolution of the Tethys Ocean. The rifting and collision events and their potential spatio-temporal relationship may play a key role in this evolution. We compiled available Permian-Jurassic paleomagnetic data from the Lhasa terrane, revealing that it drifted away from Gondwana ~210 million years ago, which is ~10 million years earlier than the South-North Qiangtang collision. Similarly, the Lhasa-Qiangtang collision preceded the rifting of India by ~10 million years. These age gaps of similar kinematic circuits align well with the time required for collision-induced subduction transference, whereby a new subduction zone forms outboard of the newly accreted terrane. Then, the slab-pull force can be transmitted to the southern segment of the younger Tethys slab by coupling across the oceanic ridge/transform system, such that subduction transference drives the in-sequence one-way convergence of microcontinents with Eurasia.

In plate tectonics, plate convergence starts with subduction initiation and stops or slows considerably when continents collide. The slab-pull force caused by oceanic slab subduction is regarded as a critical driver of plate motion[1,2]. This concept is also considered a foremost explanation for the breakup of microcontinents from Gondwana and their successive accretion onto Asia[3,4]. In the so-called one-way accretion onto Asia, each terrane moved northward from Gondwana, driven by the slab-pull force due to the subduction of the oceanic slab, until it collided with Asia. Afterwards, the northward subduction of the next oceanic slab south of the just-accreted terrane is resumed to accommodate the continuous convergence, forming a new subduction zone. This process is called collision-induced subduction transference[5,6]. Subduction transference here means the subduction is transferred from an older Tethys oceanic crust to a younger ocean on the back side of the accreted terrane, cf. Yang[5]. Notably, coupling across the oceanic ridge/transform system in the younger ocean enables the slab-pull force to be transmitted to the northern margin of Gondwana. Therefore, collision-induced subduction transference may be critical to explaining a unique feature of Tethyan evolution, i.e., the one-way (northward) convergence of a series of microcontinents from Gondwana to Asia, one after the other.

However, the potential spatio-temporal relationship between subduction transference and the plate motion cycle of unidirectional convergence remains unclear, if it exists at all. Numerical modeling has shown that the subduction initiation associated with collision-induced subduction transference generally occurs within ~10 million years (Myr) after a collision[6]. This means that if the rifting of the microcontinents from Gondwana were caused directly by subduction transference, their rifting should postdate the collision of the previous terrane with Asia by ~10 Myr. To verify this potential spatio-temporal relationship, one should first precisely constrain the kinematics, particularly the timing of the rifting and collision. The Tibetan Plateau results from the one-way northward convergence of microcontinents originating from Gondwana[7,8]; it is an unparalleled natural laboratory to constrain these kinematic scenarios. The plateau consists of the Qiangtang, Lhasa, and Himalaya terranes, separated respectively by the Bangong-Nujiang suture zone (BNSZ or Meso-Tethys) and the Yarlung-Zangpo suture zone (YZSZ or Ceno-Tethys) (Fig. 1). The terranes accreted onto the southern margin of mainland Asia in the Late Triassic[8,9], Late Jurassic-Early Cretaceous[10] and Paleocene-Eocene[11], respectively, closing the Paleo-, Meso-, and Ceno-Tethys Oceans one by one[7]. The kinematic history of the Lhasa terrane, sandwiched between the Qiangtang and Himalaya terranes by two Tethys suture zones, is thus central to the concept of one-way convergence of these terranes.

Notably, when the Lhasa terrane rifted from the northern margin of Gondwana has remained controversial for about four decades[12]. Estimates

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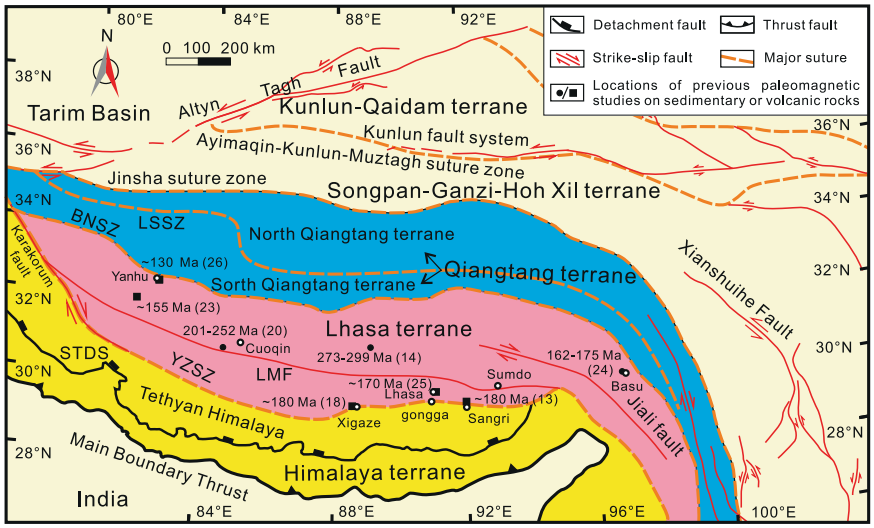


Fig. 1 | Geologic map of the Tibetan Plateau and adjacent areas (modified from Yin[8]). Indicated are the major terranes and suture zones on the Tibetan Plateau. Abbreviations: BNSZ, Bangong-Nujiang suture zone separating the Qiangtang and Lhasa terranes; LMF, Luobadui-Milashan fault, which divides the Lhasa terrane into northern and southern parts. LSSZ, Longmuco-Shuanghu suture zone, which divides the Qiangtang terrane into the North and South Qiangtang terrane; STDS, South Tibet detachment system, which separates the Tethyan Himalaya from other parts of the Himalaya terrane; YZSZ, Yarlung Zangbo suture zone, which separates the Lhasa terrane from the Himalaya terrane. Numbers (in Ma) indicate the rock ages in relevant Permian-Jurassic paleomagnetic studies[13,14,18,20,23–26]. On the map, cyan, magenta, and yellow denote the Qiangtang, Lhasa, and Himalaya terranes, respectively, while light yellow represents other blocks.

range widely from earlier than the Permian to the Late Triassic based on paleontologic, geologic, and geophysical data[13–16]. For example, some authors suggested that Lhasa drifted away from the Indian segment of Gondwana together with the Qiangtang terrane based on lower Permian mafic volcanic rocks and middle Permian overlying sedimentary strata[16]. In contrast, other research teams suggested that the Lhasa terrane rifted from Australia in the Late Triassic based on age spectra and trace element chemistry of detrital zircons[17]. However, both scenarios lack robust evidence on the drift history of the Lhasa terrane to constrain when and where it rifted from Gondwana.

The Lhasa terrane moved northward while India-Australia was moving southward during the Jurassic[13,18,19], indicating a spreading ridge (with a transform fault system) between them in this period. Therefore, the drift history of the Lhasa terrane during the Triassic-Jurassic is critical in understanding its breakup from eastern Gondwana[13,18,20]. Here, we review available paleomagnetic data from the Tibetan plateau, especially from the Lhasa terrane, combined with evidence from geology and geophysics, to strive to answer the following issues: (1) When did Lhasa rift from Gondwana? (2) Is there a potential spatiotemporal relationship between the collision and rifting events? (3) What are the dynamic implications of subduction transference and the plate motion cycle of unidirectional convergence?

Paleolatitude evolution of the Lhasa terrane during Permian to Jurassic

Reliable Mesozoic paleomagnetic data used for paleogeographic reconstruction should rely on field tests to ensure a primary natural remanent magnetization (NRM) and on enough input records to average out paleosecular variation. We suggest reliable paleomagnetic results should fulfill the following criteria based on Van der Voo[21] and Meert et al.[22], which have been widely used in paleomagnetic investigations. (1) Well-determined rock age with magnetization deemed of the same age; (2) effective demagnetization and statistical analysis with $N \geq 25$ samples for sedimentary rocks or $B \geq 8$ sites for volcanic sites; (3) reliable rock-magnetic support; (4) field tests that demonstrate the age of the magnetization; (5) reliable structural control; and (6) no resemblance to younger poles.

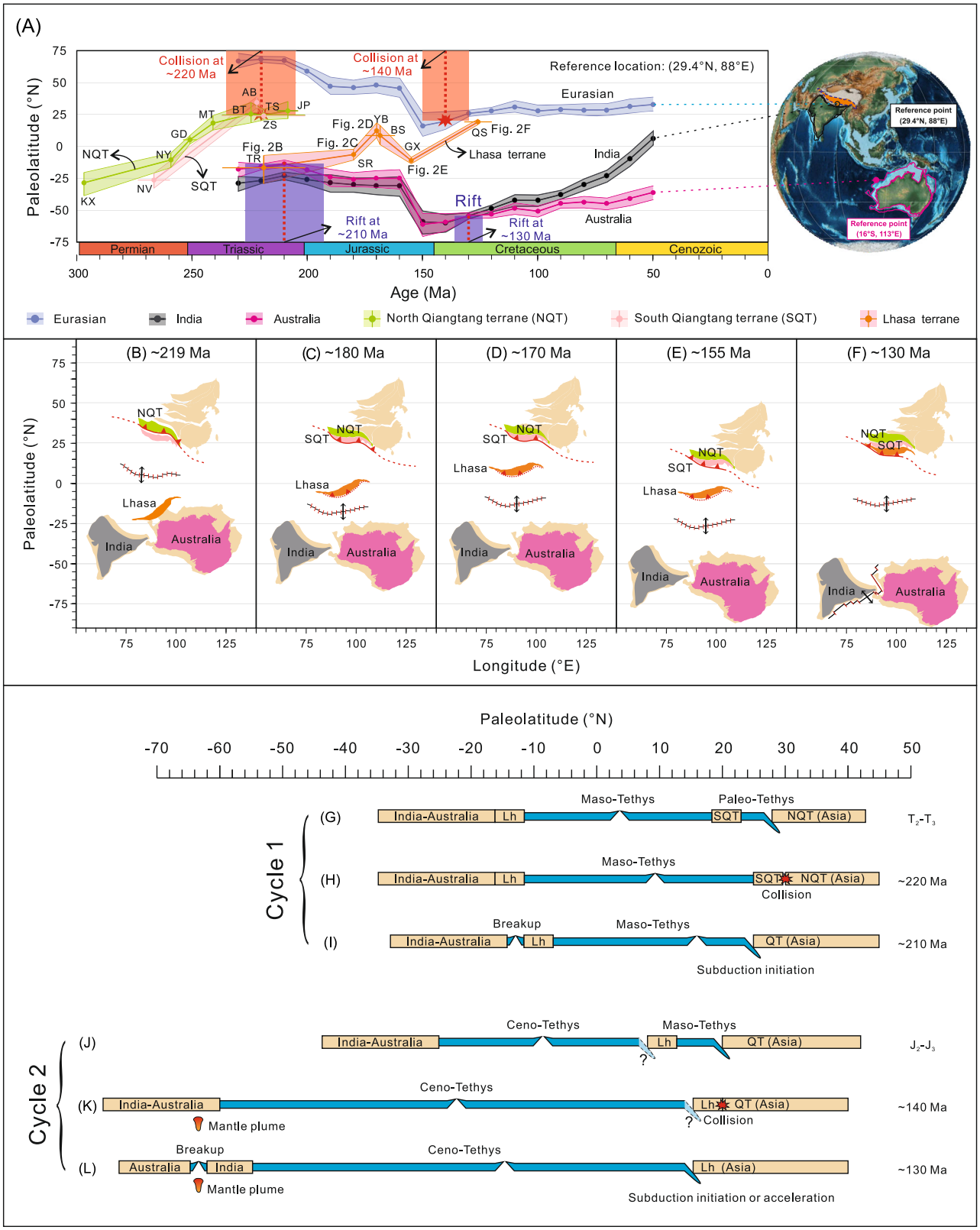
Based on our data selection criteria, some previous paleomagnetic results[14,20] from sedimentary rocks are considered questionable: their paleopoles of Permian[14] and Early-Middle Triassic[20] age are similar to that of the Late Triassic[20], violating criterion (6); presumably, those rocks are remagnetized. In contrast, the Late Triassic paleopole[20] differs from younger poles. Its positive fold test suggests a primary origin. Consequently, there is no reason to exclude it from further discussion. Thus, six pre-Cretaceous paleomagnetic results[13,18,20,23–25] are deemed reliable and used to constrain the paleolatitude of the Lhasa terrane at the reference point (29.4°N, 88°E) at the central part of the YZSZ (Fig. 2A–E) (Supplementary Table 1). The Late Triassic paleomagnetic results of six sedimentary sites (37 specimens) from the Cogen area, passing a fold test (95% confidence level), position the Lhasa terrane at 17.0° ± 10.7°S at ~219 million years ago (Ma)[20] (Fig. 2B). The Early Jurassic paleomagnetic results with positive fold and reversal tests reported by Li et al.[13] and Ma et al.[18] yield a paleolatitude of 6.6° ± 4.2°S at ~180 Ma (Fig. 2C). For the Middle Jurassic (~170 Ma), Otofuji et al.[24] and Wang et al.[25] reported paleopoles based on sedimentary and volcanic rocks, respectively, yielding a paleolatitude of ~8–12°N for the Lhasa terrane (Fig. 2D). Li et al.[23] presented a new paleomagnetic pole from the Zenong Group volcanics in the Geji area, corresponding to a paleolatitude of 11.3° ± 2.5°S at ~155 Ma (Fig. 2E).

Based on reliable paleolatitudes of 17.0° ± 10.7°S at ~219 Ma, 6.6° ± 4.2°S at ~180 Ma, ~8–12°N at ~170 Ma, 11.3° ± 2.5°S at ~155 Ma, and 18.9° ± 2.1°N at ~130 Ma (Fig. 2A), Lhasa terrane's motion during ~219–130 Ma can be divided into three stages: (1) a northward drift from the southern to the northern hemisphere from ~219 Ma to ~170 Ma, leading to the separation of Lhasa and Australia; (2) an apparent fast southward movement from ~170 Ma to ~155 Ma due to Jurassic TPW[18]; (3) a northward approach to Eurasia and collision with the Qiangtang terrane in the Late Jurassic-Early Cretaceous (~140 Ma) in the northern hemisphere. The Lhasa terrane is situated at a stable paleolatitude after the Lhasa-Qiangtang collision; it has become the southern margin of Asia (awaiting the later India-Asia collision)[26].

Lhasa terrane rifted from Gondwana at ~210 ± 14 Ma

The paleolatitude of 17.0° ± 10.7°S at ~219 Ma, which is the only reliable pre-Jurassic paleopositional constraint, agrees well with the paleolatitude of northwestern Australia[27,28] and possibly Greater India, indicating that the Lhasa terrane was most likely connected to Australia and/or Greater India at this time (Fig. 2B).

The Ceno-Tethys opened when the Lhasa terrane rifted away from the northern margin of eastern Gondwana. Therefore, understanding the drift history of both entities is central to understanding the evolution of the Ceno-Tethys. A reference point (16°S, 113°E) in northwestern Australia was chosen to assess the paleolatitude evolution of eastern Gondwana for the following reasons: (1) the northern extension of Greater India remains controversial[11], (2) India-Australia is a stable part of eastern Gondwana until ~130 Ma upon their breakoff[29], (3) India and Australia share a similar expected paleolatitude based on their apparent polar wander paths[28], and (4) the Lhasa terrane may originate from northwestern Australia based on the



similarity of zircon age profiles from NW Australia and Lhasa[17,30]. The open-source environment Paleomagnetism.org was used to calculate the respective paleolatitudes[27,28].

As shown in Fig. 2A, B, the expected paleolatitude of eastern Gondwana is ~16.3°S at 220 Ma for the reference point (16°S, 113°E), consistent with ~17.0°S at ~219 Ma of the Lhasa terrane for the reference point (29.4°N, 88°E). These overlapping paleolatitudes suggest that Lhasa and Australia were close to each other at ~219 Ma. Even though some researchers suggest that a back-arc basin was present between Lhasa and Gondwana during the Late Triassic[31], our updated paleolatitude evolution shows that this potential back-arc basin was small at ~219 Ma if it existed at all.

Fig. 2 | Reconstruction of paleolatitude, paleogeography and kinematic cycles of the Lhasa terrane and adjacent blocks. This figure shows the paleolatitude evolution (**A**) and paleo-position reconstruction (**B**-**F**) of the Lhasa terrane and adjacent blocks, including the two simplified kinematic cycles without ridge subduction (**G**–**L**). Two subduction transference events in cycle 1 (Fig. 2G–I) and cycle 2 (Fig. 2J–L) are identified in building Eurasia. The age uncertainty of the rifting events is based on paleolatitude evolution and geologic observations (see text for details). The possible southward subduction of the Meso-Tethys below Lhasa and its age remains controversial and, thus, is not indicated here to avoid confusion (See Supplementary Note 1). The exact locations of the mid-ocean ridges in the Meso-Tethys and Ceno-Tethys Oceans are somewhat uncertain; therefore, they are depicted near the centers of these oceans (Fig. 2B–F). The paleolatitude evolution is generated with www.paleomagnetism.org[28]. The observed paleolatitudes of the Lhasa, North Qiangtang, and South Qiangtang terranes are calculated from the data compiled in Supplementary Table 1. In our kinematic reconstruction, we observed a rapid TPW event during the Late Jurassic period[18] (Fig. 2A). This event is supported by several paleomagnetic data collected from continental and oceanic plates[68,69]. The Late Jurassic-Early Cretaceous TPW event formed a complete loop to provide solid evidence for the existence of fast TPW (see Hou et al.[69] and the references cited therein). Therefore, the paleolatitude evolution of Eurasia, Gondwana-India, and Gondwana-Australia are calculated from the fast TPW model based on Kent and Irving's model[27]. The paleolatitudes of Australia are calculated at a reference location (16°S, 113°E), and other paleolatitudes are calculated at a reference location (29.4°N, 88°E), cf. Supplementary Table 1[9,13,14,18,20,23–26,42–49]. An alternative scenario of subduction transference followed by ridge subduction soon afterwards, which requires the ridge to be close to the southern margin of Asia, is illustrated in Fig. 3. NQT North Qiangtang terrane, SQT South Qiangtang terrane, Lh Lhasa terrane. Other abbreviations (KX, NY, GD, etc.) indicate individual paleomagnetic results; refer to Supplementary Table 1 for full documentation.

In contrast, a paleolatitude difference of ~19.4° (~2200 km) at 180 Ma between the expected paleolatitude of ~26°S for eastern Gondwana (derived with Paleomagnetism.org) and the observed paleolatitude of ~6.6°S for the Lhasa terrane reveals the extension of the Ceno-Tethys from ~219 Ma to ~180 Ma (Fig. 2A). Interpolating the Lhasa terrane paleolatitudes of ~17.0°S at ~219 Ma and ~6.6°S at ~180 Ma[13,18] yields a terrane motion of ~3.0 cm/yr. The paleolatitude comparison between Lhasa and the northern margin of Australia during this period suggests that their separation most likely occurred at ~210 Ma (Fig. 2A). Furthermore, the ~3.0 cm/yr motion of the Lhasa terrane during the initial phase of its northward journey is significantly lower than its average motion of ~5.0 cm/yr during ~219−140 Ma or ~4.5 cm/yr during 219−130 Ma, revealing a marked acceleration of the Lhasa terrane. Therefore, the breakup age of ~210 Ma is deemed reliable. Pertaining to its uncertainty, uncertainties in paleolatitude and paleolatitude overlap are used to constrain its confidence interval. By this approach, the overlapping paleolatitudes within the confidence level indicate that their separation can be determined to no later than ~193 Ma, reflecting a 17 Myr uncertainty for the minimum age. Paleolatitude overlap cannot define the maximum separation age, because tectonic units under consideration inherently overlap when juxtaposed, cf. Figure 2A. Therefore, we use here ~210 Ma with an uncertainty of 17 Myr as the rifting age of the Lhasa terrane from Gondwana. Although this approach comes with a fairly moderate uncertainty interval, it provides the currently best possible paleolatitude evolution of the rifting, revealing that the Ceno-Tethys Ocean most likely opened at 210 ± 17 Ma. A late Triassic break-up also fits well with the rift system between the Lhasa terrane and the northern margin of Gondwana, which became mature during the late Norian[32], and with the Late Triassic (Norian/Rhaetian) to Late Jurassic (Oxfordian) extension in the Australian margin, which was accommodated in the upper crust by normal faulting and lower crustal thinning[33].

Notably, the Sumdo eclogite and arc magmatic rocks within the Lhasa terrane suggest that the Lhasa terrane can be divided into a northern and southern subterrane separated by the Tangjia-Sumdo accretionary complex zone[34]. However, the evolution and scale of the Tangjia-Sumdo Ocean remain debated[34–37]. If that ocean existed, the Lhasa terrane likely had a more complex evolutionary history. The Ceno-Tethys Ocean and/or the Tangjia-Sumdo Ocean may have opened at or before the Permian[35–37]. The Lhasa terrane may have experienced two or possibly even more rifting events from the northern margin of Gondwana[31,37,38]. The northern Lhasa terrane rifted from the southern part at early Carboniferous times based on the Early Carboniferous meta-gabbro and metabasalt from the Tangjia-Sumdo area[35]; The southern Lhasa terrane rifted from the northern margin of Gondwana at the early to middle Permian based on the extension-type magmatism Permian Yawa intrusions in the southern Lhasa terrane[39] and the middle Permian composite seamount in the Yarlung Zangbo suture zone[40]. The breakup of the southern Lhasa terrane from Gondwana might have been followed by a Triassic collision and re-breakup[38]. This potential collision and re-breakup process can explain the apparent contradictory interpretations based on paleomagnetic[13,20] and magmatic[35–37,41] evidence.

Pertaining to the Late Triassic rifting event, the only reliable pre-Jurassic paleolatitude of 17.0° ± 10.7°S for the Lhasa terrane, obtained from the northern Lhasa subterrane[20], indicates that the entire Lhasa terrane had become a coherent block by ~219 Ma and was positioned close to the northern margin of Gondwana. A unified Lhasa terrane at this time is consistent with the closure of the Tangjia-Sumdo ocean at ~240 Ma or earlier[36,37]. Therefore, we did not subdivide the Lhasa terrane in Figs. 2 and 3. Nevertheless, more reliable Permian-Triassic paleomagnetic data from the Lhasa terrane are needed to further constrain its drift history and the potential earlier opening and closing of both the Ceno-Tethys and Tangjia-Sumdo oceans.

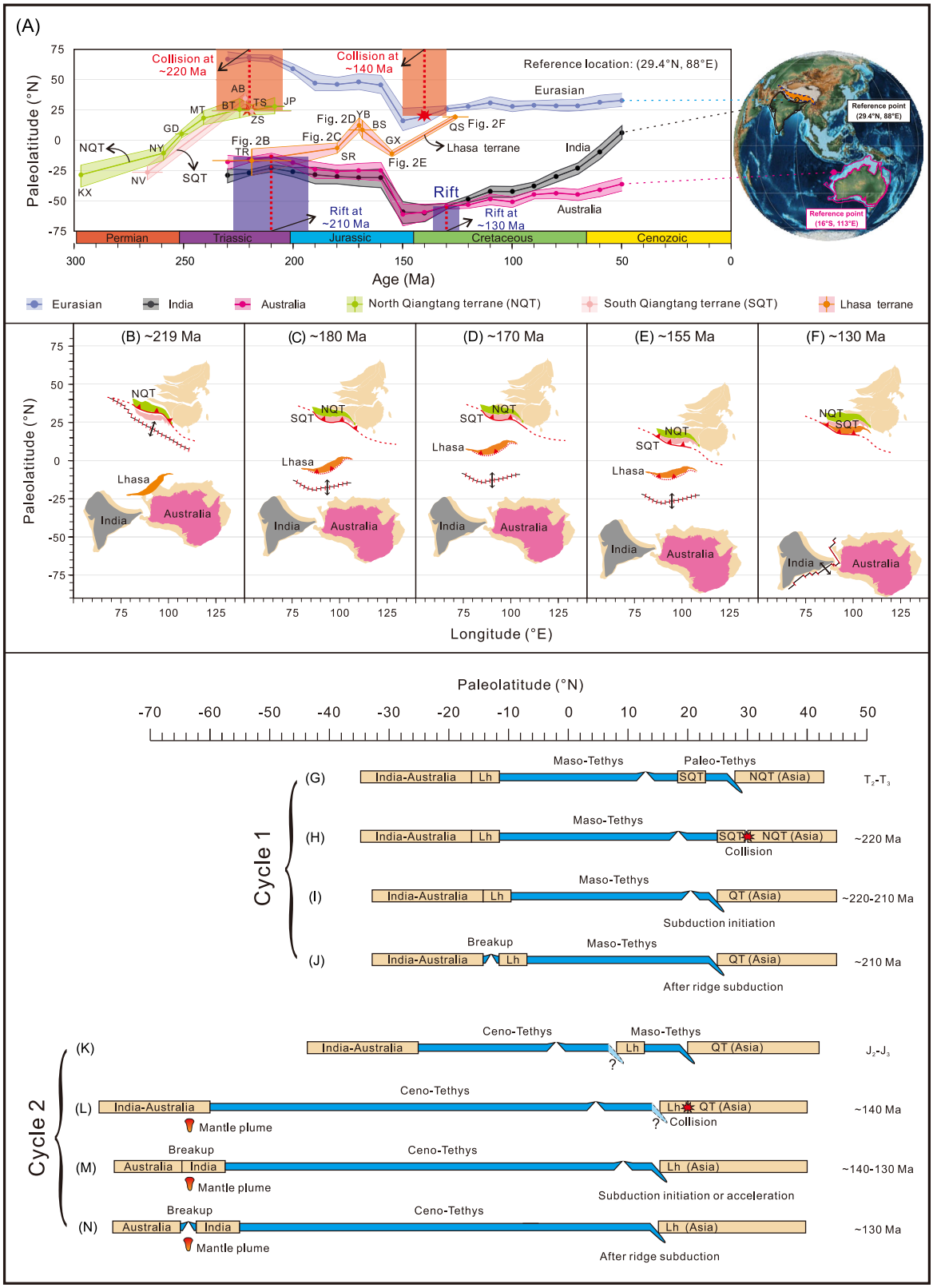
North Qiangtang-South Qiangtang collision at ~ 220 ± 15 Ma

Marked differences in lithologic character and stratigraphy, magmatism, and fossil signatures indicate that the North Qiangtang terrane (NQT) and South Qiangtang terrane (SQT), separated by the Longmu Co-Shuanghu suture zone (LSSZ), have different drift histories[9,42–48] (Figs. 1, 2). The LSSZ represents the closure of a branch of the Paleo-Tethys Ocean due to the collision between SQT and NQT. Song et al.[49] and Yu et al.[48] determined a consistent paleolatitude of ~25°N for the reference point (29.4°N, 88°E) in the Late Triassic (219 ± 18 Ma) for these terranes, forming the southern margin of Asia (Fig. 2A, H). In addition, the 230-209 Ma $^{40}Ar/^{39}Ar$ age range of high-pressure to ultrahigh-pressure metamorphic rocks and the 225-205 Ma zircon U-Pb age range of magmatic rocks in the central part of the Qiangtang terrane, whose formation may have been triggered by slab breakoff after continental collision[50], suggest that the SQT-NQT collision most likely occurred in the Late Triassic. The oldest continental sedimentary sequence of ~214 Ma unconformably overlies an ophiolite mélange of ~220 Ma in the Guoganjianian Mountain area, also pointing to a tectonic event at ~220-214 Ma at 86°E longitude[51]. The Paleo-Tethys Ocean likely closed at ~220 Ma[51]. Therefore, the collision age is conservatively estimated at 220 ± 15 Ma, with a relatively large uncertainty interval to include the age range of the magmatic flare-up and the exhumation of metamorphic rocks[50].

Lhasa-Qiangtang collision at ~140 ± 10 Ma and India-Australia break up at ~130 ± 6 Ma

The Jurassic-Cretaceous sedimentary, metamorphic, and magmatic records from the Lhasa-Qiangtang collision zone suggest that the collision most likely occurred at 150-130 Ma[52,53], which is supported by a consistent paleolatitude of Lhasa at ~130 Ma and Qiangtang at ~150 Ma (~ 20°N)[26,54]. Although reliable paleomagnetic data from ~140 Ma are lacking, provenance analysis of the Cretaceous peripheral foreland basin sediments supports a Lhasa-Qiangtang collision at ~140 Ma, quasi-simultaneously from east to west, which fits well with most of the geologic observations[52]. Therefore, the Lhasa-Qiangtang collision can be set at 140 ± 10 Ma.

Marine magnetic anomaly data from the Perth Abyssal Plain, where the oceanic crust directly records the early spreading history between India and Australia, suggests that the initial breakup occurred at ~130 Ma[55]. The



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temporal and spatial relationships between the Comei-Bunbury large igneous province and the Kerguelen mantle plume indicate that the Indian plate completely separated from the Australian-Antarctic plate before ~124 Ma[29]. Therefore, an age of 130 ± 6 Ma is used here to estimate the time of rifting of India from Australia-Antarctica.

The spatiotemporal relationship between the collision and rifting events

Pertaining to the relationship between the SQT-NQT collision and the Gondwana-Lhasa rifting, a most likely age of ~220 Ma for the collision fits well with subsequent arc magmatism in central Qiangtang that started at ~210 Ma[56,57], implying that the subduction initiation of the Meso-Tethys oceanic crust beneath the Qiangtang terrane occurred at ~220–210 Ma. The age gap between the continental collision and the subduction initiation is less than ~10 Myr, which is consistent with numerical modeling results[6]. Our paleolatitude reconstruction points to an age of 210 ± 17 Ma for the Gondwana-Lhasa rifting, i.e., 10 ± 23 Myr younger than the 220 ± 15 Ma age of the SQT-NQT collision at the southern margin of Asia (Fig. 2A). The rifting of the Lhasa terrane from Gondwana is nearly coeval with the initiation of northward subduction of the Meso-Tethys. That is, the continental collision of the Qiangtang terrane and subsequent subduction transference seem to have a potential spatiotemporal relation with Lhasa's rifting from Gondwana. In addition, this age gap of ~10 Myr is consistent with the time required for subduction initiation after a collision based on observations from the Qilian orogenic belt and numerical models[5,6], implying that subduction transference may play a vital role in the one-way terrane convergence from Gondwana to Asia. This 10 Myr age interval is also consistent with the age interval documented for subduction reversal (similar to outboard jumping of the subduction zone, but with a change in the polarity of the slab) in several other orogens[58].

For the relationship between the Lhasa-Qiangtang collision and the India-Australia rifting, a similar spatiotemporal relationship exists. There is an age gap of 10 ± 12 Myr between the Lhasa-Qiangtang collision and the rifting of India. The similar spatiotemporal relationship between the collision and rifting events with similar age gaps of ~10 Myr can be well explained by collision-induced subduction transference, which has been demonstrated by observation and numerical modeling. Next, we focus on whether ridge coupling is a required component in the scenario, explore alternatives, and discuss the first-order dynamics of the in-sequence northward convergence of the Tethys evolution.

Coupling across the oceanic ridge/transform system model

The spatiotemporal relationship between the continental collision and the microcontinent rifting can be explained by collision-induced subduction transference. But how can the slab-pull force on the northern margin of Tethys fit with the rifting on its southern margin? Coupling (at least partial) must exist across the oceanic ridge/transform system within the ocean, so that the slab-pull force caused by collision-induced subduction transference in the north can be at least partly transmitted to the southern segment of the Meso- or Ceno-Tethys Ocean, triggering the rifting of Lhasa or India.

This effect (coupling across the oceanic ridge/transform system) should not be neglected and is supported by plate reconstructions. For example, the Pacific plate was bound to the north by spreading ridges but moved northward at high velocity during ~85–55 Ma[59,60]. Because the high velocity cannot be explained plausibly otherwise, the slab-pull force of the subducting Izanagi plate to the north of the ridge with (partial) coupling across the ridge/transform system should be invoked. In the Tethyan realm, since an oceanic ridge is typically offset by transform faults, the latter thus also connected the southern and northern parts of the Meso- or Ceno-Tethys. The geometry and orientation of the ridge/transform system in the Meso- and Ceno-Tethys oceans are not well determined, and different orientations of the ridge and transform segments would lead to different amounts of coupling. It has been suggested that the transform fault strength rheologically may be just slightly weaker than that of its surrounding plates[61], in particular under normal stresses, and the amount of coupling would also depend on the orientation of the ridge/transform system relative to the new subduction zone. The rheological strength of a transform fault/fracture zone system may thus be sufficient to transmit stress, due to (strong) coupling through the transform faults[62,63], in particular, if these structures are at an angle about the tensional stresses induced by the slab-pull. Recent numerical models on trench-parallel oceanic ridge subduction also indicate that the transform fault and fracture zone should not be too weak for the lateral transmission of slab pull across the ridge[63]. Therefore, neighboring oceanic plates, separated by a ridge, are not totally decoupled[63]. Coupling across the ridge makes it possible for the slab-pull force to be transmitted, which is an important ingredient of the spatiotemporal relationship illustrated by our reconstruction. In this scenario, the cycles of the collision and rifting can be reconstructed as depicted in Fig. 2G–L (i.e., without having to invoke an early ridge subduction).

Ridge subduction model

An alternative scenario for the observed spatiotemporal relationship may be ridge subduction soon after subduction transference, so that the slab-pull force can really be transmitted to the (originally) southern segment of the Meso- or Ceno- Tethys Ocean, triggering the rifting of Lhasa and India (Fig. 3).

The Eurasia-directed subduction of the oceanic spreading centers in the north of the Tethys Oceans may influence the fragmentation of Gondwana. In an ocean with an Andean-type subduction zone, it is straightforward to subduct ridges. This is because all the subduction must be accommodated by the trench-ward motion of the subducting (oceanic) plate. This is the case in the Pacific today and might have been even more pronounced in the Tethyan realm, where plate velocities >10 cm/yr have been reported. Therefore, collision-induced subduction transference and ocean ridge subduction shortly after collision may be an alternative explanation for the spatiotemporal relationship.

Ridge subduction soon after subduction transference can also explain the age gap of ~10 Myr between the SQT-NQT collision and the Gondwana-Lhasa rifting (Fig. 3G–J). After subduction transference, the ridge migrates towards the direction of most rapid subduction, especially in an ocean like the Tethys, which is bordered by a passive continental margin to the south and an active continental margin to the north[8]. This interpretation can also be supported by plate reconstructions. For example, Scotese[59] reconstructed the mid-ocean ridge of the Meso-Tethys close to the southern margin of Asia in the Late Triassic (Fig. 3B, H, I), supporting the fast subduction of the oceanic ridge below Asia scenario which enables the slab pull force being transferred to the passive margin of Gondwana which triggers the rifting of the Lhasa terrane (Fig. 3J).

For the age gap of ~10 Myr between the Lhasa-Qiangtang collision and the rifting of India, the ridge is subducted shortly after the transference so that the slab-pull force can be transmitted to the southern edge of the Ceno-Tethys. In this scenario, the ridge is close to the southern margin of Asia (Fig. 3L, M). This scenario is also supported by plate reconstructions. Zhang et al.[64] suggest the ridge was close to the active continental margin during the Early Cretaceous based on paleomagnetic data of the Xigaze ophiolites in the Gangdese forearc[65], supporting subduction of the northern segment of the Ceno-Tethys and the ridge at ~130 Ma (Fig. 3M, N). After subduction of the ridge, the slab-pull-force was transferred from the Meso-Tethys to the southern segment of the Ceno-Tethys (Fig. 3K–N), dragging India to rift from Australia-Antarctica at 130 ± 6 Ma.

In the scenario depicted in this section, the ridge should be close to the southern margin of Asia (Fig. 3). Given that the reconstruction of a ridge's position is subject to uncertainty, coupling (either full or partial) across the ridge/transform system may be a more likely scenario. In addition, the southward subduction model for the rifting of the Lhasa terrane is considered an option for potential debate on the existence and age of the southward subduction[15,31,66] (See Supplementary Note 1). Nevertheless, subduction transference is vital in all these models to explain the in-sequence one-way convergence of microcontinents with Asia.

Dynamics of the in-sequence northward convergence

In summary, two similar geodynamic cycles are identified—both including the northward convergence of the Gondwana-derived terranes (Fig. 2G, J, and Fig. 3G, K), their collision with Asia (Fig. 2H, K, Fig. 3H, L), collision-induced subduction initiation [(or acceleration) see Supplementary Note 2)] of the younger Tethys slab (Fig. 2I, L, and Fig. 3I, M) and the breakup of the next terrane from Gondwana (Fig. 2I, L) [after a fast ridge subduction (Fig. 3J, N)].

The evolution of an ocean basin from opening to closing is referred to as a Wilson cycle. The opening to the closing cycle of the Paleo-, Meso-, and Ceno-Tethys Oceans thus correspond to three successive "Wilson cycles". The Paleo-Tethys here only refers to a branch of the Paleo-Tethys (Longmu Co-Shuanghu Ocean) that opened between the NQT and SQT based on their different drift histories, but it does not refer to another branch of the Paleo-Tethys (Jinshajiang Ocean) between the Qiangtang terrane and the Tarim-Qaidam Blocks. Given the same age gap of ~10 Myr for the "collision-subduction transference-rift" process, we refer to these processes that linked three successive Wilson cycles as "Linked-Wilson cycles" (Fig. 2). The dynamics of each Linked-Wilson cycle can be summarized as follows. Before each terrane collision, the respective oceanic plates continued to be subducted beneath Asia due to the slab-pull force, pulling the micro-continent northward. When a positively buoyant terrane (or micro-continent) collides with the southern margin of Asia, an active continental margin, the subduction zone to the north of the accreted terrane becomes clogged because the positively buoyant continental lithosphere has difficulty continuing subduction like the oceanic lithosphere[5]. After the continental collision, however, the Tethyan oceanic crust to the south of the collided terrane continued to move northward after the subduction zone stepped out to the outboard side of the accreted terrane. In this process, stress concentration occurred at the junction between the Tethyan Ocean and the new southern margin of Asia, positioning the junction ideally for potential subduction initiation[6,67]. The slab-pull force caused by subduction transference can be transmitted to the northern margin of Gondwana through coupling across the ridge/transform system, triggering rifting and the northward motion of microcontinents from Gondwana to Asia. Subduction of the ridge eventually facilitates the northward drift of the microcontinents.

The similar spatiotemporal relationship revealed by the Linked-Wilson cycles suggests that subduction transference and/or acceleration plays a vital role in the one-way convergence from Gondwana to Asia, at least for the Tibetan realm. The fate of the Wilson cycle of the respective terranes was probably sealed before it even began.

Data availability

All study data are included in the article and/or supporting information, including Supplementary Notes 1 and 2 and Supplementary Table 1. These data can be download at files section at https://doi.org/10.17605/OSF.IO/RN3FA.

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Author contributions

Y.M., M.J.D., J.D., and T.K. wrote the paper.

Competing interests

The authors declare that they have no competing interests. João C. Duarte is an Editorial Board Member for Communications Earth & Environment, but was not involved in the editorial review of, nor the decision to publish this article.

Additional information

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