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To cite this version:
Jan Westerweel, Pierrick Roperch, Alexis Licht, Guillaume Dupont-Nivet, Zaw Win, et al.. Burma Terrane part of the Trans-Tethyan arc during collision with India according to palaeomagnetic data. Nature Geoscience, Nature Publishing Group, 2019, 12 (10), pp.863-868. 10.1038/s41561-019-0443-2.

HAL Id: insu-02283010
https://hal-insu.archives-ouvertes.fr/insu-02283010
Submitted on 16 Nov 2020

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Burma Terrane part of the Trans-Tethyan arc during collision with India according to palaeomagnetic data

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Convergence between the Indian and Asian plates has reshaped large parts of Asia, changing regional climate and biodiversity, yet geodynamic models fundamentally diverge on how convergence was accommodated since the India–Asia collision. Here we report palaeomagnetic data from the Burma Terrane, which is at the eastern edge of the collision zone and is famous for its Cretaceous amber biota, to better determine the evolution of the India–Asia collision. The Burma Terrane was part of a Trans-Tethyan island arc and stood at a near-equatorial southern latitude at ~95 Ma, suggesting island endemism for the Burmese amber biota. The Burma Terrane underwent significant clockwise rotation between ~80 and 50 Ma, causing its subduction margin to become hyper-oblique. Subsequently, it was translated northward on the Indian Plate by an exceptional distance of at least 2,000 km along a dextral strike-slip fault system in the east. Our reconstructions are only compatible with geodynamic models involving an initial collision of India with a near-equatorial Trans-Tethyan subduction system at ~60 Ma, followed by a later collision with the Asian margin.

The palaeogeographic evolution of the Burma Terrane (BT, also named the West Burma Block) at the eastern edge of the collision zone differs in these geodynamic scenarios and therefore offers a way to determine the most realistic model (Fig. 1). In the continental Greater India models5,12, the BT is located at a relatively high latitude during the Palaeogene, next to the Lhasa Terrane as part of a linear and approximately east–west-oriented Asian margin. From this position, the BT is extruded towards its present-day location. The volcanic Wuntho-Popa Arc of the BT was interpreted as the eastward continuation of the Gangdese magmatic arc required in these models; however, the arc is currently oriented approximately north to south (Fig. 2). Therefore, these models necessitate significant post-collisional clockwise rotation for the BT. In the oceanic Greater India models5,12, the Asian margin is less deformed during the collision and the BT experiences little post-collisional rotation. Finally, the position of the BT is less constrained in the Trans-Tethyan subduction models. Most reconstructions involving double subduction show the BT north of Sumatra13,17, but it could have also been part of the Incertus Arc, the island arc of the Trans-Tethyan subduction system17, which would potentially allow a more southern latitude for the BT during the earlier periods of collision5,13,16,17.

Presently, the palaeogeographic evolution of the BT is virtually undocumented, despite being of critical importance for biodiversity studies; the fossil amber from the BT harbours one of the most diverse and largest known records of Cretaceous biota16,18. Furthermore, the palaeogeography of the BT is important for palaeoenvironmental studies investigating Asian monsoon history20,21. This study aims to fill this gap and solve these controversies by providing necessary constraints on the motion of the BT using new palaeomagnetic and 40Ar/39Ar age data.

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Geology of the Burma Terrane

The present-day BT geodynamic setting is characterized by hyper-oblique subduction of the Indian plate below the Burmese margin in the west and by the large-scale, active dextral strike-slip Sagaina Fault in the east, resulting in a northward transient motion of the terrane. The western boundary of the BT is delineated by either another strike-slip fault (the Kabaw Fault) or the Naga Hills–Kaleymyo–Andaman Ophiolite (herein called the Western Belt Ophiolite) in the Indo-Burman Ranges (IBR)\(^{35,36}\). The IBR basement has been interpreted as either (1) a separate tectonic block accreted to the BT either in the Early Cretaceous\(^{37}\) or in the Late Cretaceous to Palaeogene\(^{38,39}\) or (2) an accretionary-type setting without block collision\(^{40,41}\). East of the BT, there is a complex succession of metamorphic rocks (the Mogok–Mandalay–Mergui Belt, or MMIB) that forms the boundary of the BT with the Jade Belt Ophiolite\(^{31}\). The complete dextral displacement along this fault system has been estimated to be between 400 and 1,100 km (refs. 36–43). Before the development of the Sagaina Fault, there is evidence for dextral deformation along the Shan Scarp, directly east of the Sagaina Fault\(^{33,34}\), although the tectonic regime of the Sibumasu Block was predominantly sinistral\(^{41}\). Another example of earlier dextral deformation is the late Oligocene West Andaman Fault to the south\(^{44}\).

The oldest exposed rocks of the BT are the low-grade metamorphic Triassic Shwedaung and Pane Chaung Formations, as well as the higher-grade Kankpetit Schist. Both a late Mesozoic Gondwanan\(^{36}\) or Cathaysian\(^{37}\) origin has been suggested for the Pane Chaung Formation based on the detrital zircon uranium-lead (U-Pb) age data. The Burmese margin formed an Andean-type setting during the Cretaceous, as evidenced by Andean-type magmatic activity in the Wuntho-Popa Arc that today crops out in the middle of a wide belt of forearc and back-arc basins, which developed contemporaneously in central Myanmar (Fig. 2)\(^{36,37,38}\). Published U-Pb data indicate an early Late Cretaceous main phase of magmatism from 110 to 85 Ma, followed by a subordinate stage from 40 to 70 Ma (refs. 24,27,36,40). Our new 97 to 87 Ma \(^{40}Ar/^{39}Ar\) dates in the Kanza Chaung Batholith, the main unit of the northern Wuntho-Popa Arc (Fig. 2, Supplementary Dataset 1), confirm this major magmatic phase. The Western Belt Ophiolite was probably emplaced during that time as well\(^{31,27,25,34,31}\). The Wuntho-Popa Arc has been correlated with the similar Gangdese Arc (Lhasa Terrane)\(^{34,37}\). The correlation of (1) the Gangdese Arc with the Wuntho-Popa Arc and (2) the Western Belt Ophiolite with the Tibetan Yarlung-Tsangpo Suture Zone\(^{40,43}\) are key arguments for the BT to have been located at a latitude similar to the present day and for its position to have been next to the Lhasa Terrane before the India–Asia collision. However, the Mawgyi Andesite, which is most likely part of the Wuntho-Popa Arc (see Supplementary Information), has been correlated with the intra-oceanic mid-Cretaceous Woyla Arc (Sumatra)\(^{21,23,30}\) as part of the Incertus Arc (Fig. 1)\(^{17}\). Subsequent studies continue the Incertus arc farther west by incorporating the Kohistan Arc (Pakistan)\(^{44,45}\).

Palaeomagnetic study

A palaeomagnetic pole was obtained from a homoclinal sedimentary sequence in the late Eocene (~38 Ma from a dated tuff layer\(^{46}\)) shallow-marine Yaw Formation in the Chinbwin Basin, the northernmost forearc basin of Myanmar (Fig. 2). Furthermore, an early Late Cretaceous pole was obtained from five localities (Pinelebu, Shinta, Banmauk, Kawlin and Kyaung Le) in the Wuntho Range, which is the predominantly Cretaceous (~110 to 85 Ma (refs. 24,40)) northern segment of the Wuntho-Popa Arc, where the volcanic and sedimentary rocks of the Kondan Chaung Group are intruded by igneous (I-type) intrusions (Kanza Chaung Batholith) and andesitic stocks (Mawgyi Andesite). Detailed information on the geology, palaeomagnetic analysis and \(^{40}Ar/^{39}Ar\) dating is provided in the Methods, Supplementary Information and Supplementary Datasets 1–3.

The late Eocene samples are from mudstones and siderite beds with primary detrital or early-diagenetic magnetizations, mostly carried by magnetite. They yield well-defined antipodal normal and reverse-polarity directions in coherent magnetozones, resulting in a mean with a north-oriented declination and shallow positive inclination in tectonic coordinates (Fig. 3a, Supplementary Dataset 1). This mean palaeomagnetic direction corresponds to a negligible rotation (4.6 ± 3.5°) compared to stable Eurasia\(^{42}\) and a near-equatorial latitude of 2.4 ± 1.5°N. A slightly higher, but not significantly different 4.1 ± 2.3°N palaeolatitude is obtained after inclination-shallowing corrections (see Supplementary Information). This result is corroborated by similarly low inclinations obtained from the siderite beds devoid of shallowing, and it is in general agreement with the low impact of inclination shallowing in sedimentary rocks at low latitudes when compared to middle to high latitudes\(^{41}\).
In early Late Cretaceous rocks from the Wuntho Range, reliable directions were obtained from the Konda Chaung Group, but occurred before the intrusion of the batholith in most cases. No field evidence for significant tilting of the Kanza Chaung Batholith was observed, which is in agreement with our anisotropy of magnetic susceptibility data (see Supplementary Information). If we omit data from brecciated and non-homogenously hydrothermally altered sites from the Mawgyi Andesite (Kawlin) and the westemmost sites from the Konda Chaung Group (Kyaung Le), which were slightly tilted after acquiring their magnetization, we obtain a similar but better defined overall final mean direction for the Wuntho Range from 16 sites (Fig. 3b, Supplementary Dataset 1). The mean corresponds to a slightly southern hemisphere palaeolatitude of 5.0 ± 4.7°S for the BT in the early Late Cretaceous and a significant clockwise rotation (60.4 ± 8.7°) with respect to the expected direction from stable Eurasia. Although we cannot discard a component of local rotation associated with dextral shear, the systematic rotation values and the regionally coherent north-south trends of the batholith and main tectonic structures suggest that the mean declination better reflects a complete rotation of the BT. The different palaeomagnetic results for the Chindwin Basin and the Wuntho Range imply that most rotation of the BT occurred between the early Late Cretaceous and late Eocene with ~800 km of northward motion (Fig. 3c). The near-equatorial early Late Cretaceous to late Eocene palaeolatitudes implied by our data are in stark contrast to previous studies, usually placing the BT close to its present-day location since the early Cenozoic and these data therefore have major tectonic implications.

**Tectonic implications**

The southern hemisphere shallow latitude at ~95 Ma for the Wuntho-Popa Arc was distant from the southern Asian margin and Indochina and is therefore best explained as having been formed above a near-equatorial Trans-Tethyan subduction system, as part of the Incertus Arc, with northward-subducting Neo-Tethyan oceanic lithosphere (Fig. 4). This interpretation is further supported by the development of the Burmese margin as an Andean-type setting around that time (Late Cretaceous) and coeval emplacement of the Western Belt Ophiolite. The Trans-Tethyan subduction system could have been partly intra-oceanic, possibly incorporating the Kohistan Arc, which also formed at a near-equatorial latitude. Because the Indonesian Woyla Arc is interpreted as having been already accreted at ~90 Ma (refs. 17,21), we reconstructed a transform fault east of the BT, accommodating an earlier collision between the Woyla Arc and the Sundaland Block.

The major clockwise rotation of the BT between 95 and 40 Ma (Fig. 4) may have been linked either to the accretion of the BT to the margin of the southern Sibumasu and northern Sundaland Blocks or to the collision of India with the Trans-Tethyan subduction system. In support of the latter possibility is that in most models with Trans-Tethyan subduction8,13,16, decreasing convergence rates between India and Asia at ~60 to 50 Ma are associated with a collision of the (Greater) Indian continent with the arc. At the eastern end of this collision, the thin Indian continental crust may thus have interacted with the BT, causing its clockwise rotation. However, the exact timing and mechanism of this rotation needs to be refined with future research.

Since the late Eocene (~38 Ma (ref. 21)), our results indicate a significant ~2,000 km northward motion, coeval with the motion of India (Fig. 4), during a period when Indochina was extruded towards the southeast46-49. The results suggest that the northward motion of the BT was coupled with the Indian Plate. Our palaeo-
magnetic data indicate that the Burmese subduction margin was already oriented approximately north-south in the late Eocene, such that subduction of the Indian Plate beneath the BT was already hyper-oblique. This hyper-obliquity provided a mechanism for the full partitioning of the Burmese subduction margin relative to Indochina and its coupling with the Indian motion; it is also consistent with the inferred onset of pull-apart subsidence in the Chindwin Basin and a significant decrease in Wuntho-Popa Arc magmatism at ~38 Ma (refs. 24,40). Furthermore, the coeval motion of the BT and India suggests that dextral wrenching within the IBR was not important until the Neogene. Hence, the northward motion of the BT since the late Eocene required a major dextral strike-slip system east of the BT. However, the ~2,000 km of northward motion indicated by our palaeomagnetic data is much more than the ~400 km of motion estimated along the active dextral Sagaing Fault at the eastern margin of the BT. Furthermore, the age of the Sagaing Fault (Quaternary, Neogene or older) remains debated10–12. A precursor dextral strike-slip system is thus required by our data, the pathway and location of which remains enigmatic and has probably been obscured by posterior activity of the Sagaing Fault and the opening of the Andaman Sea. The potential remnants of this precursor strike-slip system are an early segment of the Sagaing Fault or the Oligocene West Andaman Fault. The latter could have effectively separated the BT to its west from the developing Eastern Andaman Basins and the predominantly sinistral tectonic regime of the Sibumasu Block to its east as the BT moved northward and passed west of these features (Fig. 4). This separation potentially explains why the late Eocene sedimentary infill of the Central Myanmar Basins was predominantly derived from an Andean-type arc, probably the Wuntho–Popa Arc, with an increasing contribution of older metamorphic detritus in the Oligocene and Miocene as the BT moved closer to the Sibumasu Block and the eastern Himalayan syntaxis. Additionally, the low late Eocene palaeolatitude for the BT demonstrates that an India–BT collision next to the Lhasa Terrane was impossible. Instead, the near-equatorial latitude of the BT provided the space and free border for the lateral extrusion of the Tengshong and Baoshan Blocks, which rotated clockwise by ~40° to 70° (refs. 27,40) and, to a minor extent, the Indochina Block, which rotated ~15° to 20°, all of which occurred mainly during the Oligocene and Miocene. The Oligocene and Miocene included periods of major sinistral deformation along the main shear zones separating these blocks16,49. The northward motion and later emplacement without rotation of the BT also accounts for the striking difference between the linear north-south orientation of the Sagaing Fault and, directly to the west, the curvilinear sinistral faults (Gaoligong, Wanding, Nanting) associated with the clockwise rotations in the Tengshong and Baoshan Blocks. Beyond geodynamics, our results suggest that the BT was isolated as part of the Incertus Arc at the time of deposition of the prolific Cretaceous Burmese fossil ambers, which raises questions about the potential endemic character of the amber biota and their connection with species from India, Gondwana and southeastern Asia18,19. From a palaeoenvironmental perspective, our near-equatorial palaeolatitudes for the BT are surprising, considering the evidence for a strongly seasonal climate in Myanmar in the Eocene. Strong seasonality at Eocene equatorial latitudes in southeastern Asia is corroborated by independent evidence from palaeoclimatic data from Java50. Palaeomagnetic and palaeoenvironmental data can only be reconciled with a massive seasonal migration of the Intertropical Convergence Zone over southeastern Asia, confirming well-marked South Asian monsoons during the Eocene; however, future climate models incorporating our new reconstructions will be needed to verify the migration.
The foremost conclusion from our palaeomagnetic results is that they are incompatible with both continental and oceanic Greater India models and are best interpreted in a geodynamic framework with a Trans-Tethyan subduction system accommodating India–Asia convergence. As part of this system, the BT was a segment of the Incertus Arc when Neo–Tethyan subduction began in the Late Cretaceous. In the period that included the early Palaeogene collision of India with the Trans-Tethyan subduction system, the BT rotated ~60° clockwise and then moved northward at least 2,000 km since ~38 Ma as part of the Indian Plate along a dextral strike-slip system until it reached its present-day position. Hence, our findings provide much-needed evidence to settle a longstanding geodynamic debate on the India–Asia collision and the existence of a Trans-Tethyan subduction system. Furthermore, they pave the way to a reinterpretation of regional structural and palaeogeographic data by taking into account the near-equatorial position of the BT during the Late Cretaceous to Eocene as part of this system.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of code and data availability and associated accession codes are available at https://doi.org/10.1038/s41561-019-0443-2.

Received: 2 November 2018; Accepted: 2 August 2019; Published online: 9 September 2019

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Acknowledgements

This research was primarily funded by the European Research Council’s consolidator grant MAGIC (Monosons in Asia caused Greenhouse to Icehouse Cooling) no. 649081 to G.D.-N. We thank C. Kissel for the use of the AGM magnetometer at the Laboratoire des Sciences du Climat et de l’Environnement’s palaeomagnetic laboratory, France. Furthermore, we thank I. Joanny and F. Goutet for their help with scanning electron microscope data acquisition. We are grateful to P. Cullierie and A. Bernard for their help in the laboratory. We thank E. Advokaat, F. Fluteau, S. Guillot, E. Hallot, C. Rangin, A. Replumaz, M. Searle and D. van Hinsbergen for prolific discussions in the course of this study. Finally, we are grateful to C. Morley, R. Hall and J. Geissman for their constructive comments, which helped to clarify our data presentation and model.

Author contributions

P.R., A.L. and G.D.-N. conceived the project. J.W., P.R., A.L., G.D.-N., Z.W.F., H.H.S., M.K.T. and D.W.A. participated in the sampling. J.W. and P.R. performed the palaeomagnetic analysis. G.B. performed the radiometric analysis. J.W., P.R. and F.B. built the GPlates model. J.W., P.R., A.L. and G.D.-N. wrote the manuscript with contributions from other authors.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41556-019-0443-z.

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Methods

Palaeomagnetic sampling. Conventional palaeomagnetic core plug samples were obtained from two localities in the BT in northern Myanmar. Sampling and determining the orientation of the samples were done using standard palaeomagnetic field equipment and procedures with both magnetic and sun compasses. The first locality covers the early Late Cretaceous intrusive, extrusive, volcanioclastic and sedimentary rocks of the Wuntho Range near the town of Kawlin, Pindleu, Shinga, Banmauk and Kyaung Le. The second locality includes the late Eocene sedimentary rocks of the Chindwin forearc basin near the town of Kalewa. A detailed geologic setting, including regional maps, is described in the Supplementary Information.

We sampled 19 sites in intrusive rocks, 13 sites in extrusive rocks and 9 sites in sedimentary rocks of early Late Cretaceous age in the Wuntho Range; most samples were obtained by drilling into recently exposed quarries or rivers, providing fresh samples with almost no weathering. Most samples from the intrusive rocks were obtained around Pindleu, Shinga and Banmauk in the western and northern part of the study area. These samples were taken from the regional 1-tpe Kanza Chaung Batholith, which constitutes the main component of the Wuntho Range. Near Kawlin in the southern part of the study area, 11 sites were taken from extrusive rocks of the Mawgyi Andesite Formation. The volcanic rocks were often and completely brecciated; hence, they did not yield clear bedding orientations. Apart from these anesities, two sites were obtained near Kawlin from sandstones of the volcanic-sedimentary Kondan Chaung Group, which was characterized by clearly observable bedding, and one undetermined site. At Kyaung Le in the northernmost part of the study area, all sites were obtained from the Kondan Chaung Group and consisted of nested sedimentary and volcanioclastic rocks, one rhyolitic igneous rock, one brecciated undivined extrusive rock.

In the Chindwin Basin, 520 samples were collected from the late Eocene shallow-marine Yaw Formation in a continuous homoclinic Cenozoic sedimentary section near Kalewa, as well as from two additional sites. Most of these samples were mudstones and sandstones, and we also collected several samples in siderite-rich carbonate beds intercalated in the mudstones.

Palaeomagnetic analysis. Natural remanent magnetizations were measured on a 2G cryogenic magnetometer hosted in a magnetically shielded room at the University of Rennes 1. Stepwise demagnetization was used to isolate their ChRM components using either (1) thermal demagnetization, with increments of 20°C up to 30°C or up to 680°C or (2) 3-axis alternating field demagnetization, with increments of 2.5 mT up to 1200 mT. During the alternating field demagnetization, the gyroremagnetizations were cancelled by measuring the magnetization after each axis of alternating field demagnetization. Samples with interpretable components were grouped by site after isolating their ChRM using principal component analysis and, when necessary, a great-circle approach. Subsequently, mean directions and corresponding statistical parameters were calculated by site and finally by locality using Fisher statistics. Whenever possible, the fold test was used to investigate whether the magnetization was pre- or post-tectonic in origin. To check whether normal and reverse polarities from the same locality were antiparallel, the classic coordinate bootstrap reversal test was used. Finally, due to the lack of volcanic rocks in the late Eocene sedimentary section, we checked for inclination shallowing in the results from this area by using several techniques including (1) the classic elongation versus inclination method and (2) an assumption that the sedimentary package consists of uniform rigid particles, which rotate during burial and attending compaction.

In addition to obtaining mean directions, the magnetic properties of the samples were investigated using several methods. After each thermal demagnetization step, the bulk magnetic susceptibility of the samples was measured. To investigate the mineralogy and magnetic properties for a selection of samples, we measured mass-normalized bulk magnetic susceptibility curves with increasing temperature steps up to 580°C on a KLY3-CS3 AGICO Kappabridge, as well as magnetic hysteresis loops on an alternating gradient magnetometer (AGM 2900). To further identify the possible effect of a magnetic fabric on the remanent magnetization for the different rocks, the anisotropy of magnetic susceptibility was determined for most samples on a KLY3S AGICO Kappabridge. In highly anisotropic intrusive igneous rocks, thermal remanent magnetization vectors may be deflected from the direction of the field upon cooling below the Curie point of magnetite, which was the main magnetic carrier in those rocks. However, most of the anisotropy of magnetic susceptibility was probably dictated by multidomain magnetite, yet the magnetic carriers of the remanent magnetization (the finest grained magnetite) may have had a different magnetic fabric. For this reason, we investigated the anisotropy of remanent magnetization in selected samples of intrusive rocks. The thermal remanent magnetization anisotropy correction is common in palaeomagnetism, but we did not attempt this because it requires heating the samples above 580°C (the general natural remanent magnetization unblocking temperature) and alteration is likely to occur after heating to higher temperatures. The anisotropy of isothermal remanent magnetization was performed on selected samples instead. The isothermal remanent magnetization acquisition was done on x-y-z, then y-z, then x-z at 600 mT, well above the saturation field of magnetite (250 mT). After each measurement, the sample was alternating field demagnetized at 20 mT to remove the lowest magnetic coercivity fraction. In most cases, 90% of the full isothermal remanent magnetization was randomized at 20 mT.

A detailed description of the various ChRM characteristics, mean calculations, tests and magnetic properties is given by locality in the Supplementary Information. The palaeomagnetic results by site and locality are given in Supplementary Dataset 1 the results from all samples are listed in Supplementary Dataset 2.

Petrology. Polished thin sections were made from selected samples from different lithologies for observation under an optical microscope in transmitted light and reflected light. The samples were then analysed with a scanning electron microscope (JEOL JSM 7100F with Oxford energy dispersive X-ray spectroscopy and electron backscatter diffraction) at the Centre de Microscopie Électronique à Balayage et Microanalyse–ScanMAT platform (University of Rennes 1). Our petrologic observations are described in the Supplementary Information.

\*Az\*\*Ar\* dating. There are only a few available U-Pb age data available for the Wuntho Range volcanic complex. Therefore, we carried out \*Ar\*\*Ar\* dating on 14 samples from our palaeomagnetic sites in order to better understand the ages of these rocks and their resulting CRMs. The samples were analysed with an \*Ar\*\*Ar\* laser probe and a Map 215 mass spectrometer. Analyses were performed on millimeter-sized grains of single biotite or amphibole crystals, carefully handpicked under a binocular microscope from crushed rocks. For samples with a fine-grained matrix from which it was not possible to extract biotites or amphiboles, experiments were performed on whole-rock samples.

The irradiation of the samples was performed at the McMaster Master Reactor (Hamilton, Ontario, Canada) in the 8F facility and lasted 66.667 h with a global efficiency (f’ h’ –1) of 9.767 x 10^-6. The irradiation standard was sanidine from the Taylor Creek Rhyolite (28.688 ± 0.033 Ma (refs. 86–88)).

Apparent age errors were plotted at the 1 σ level and do not include the errors on the \*Ar\*\*Ar\* ratio and age of the monitor and decay constant. Plateau ages were calculated if 70% or more of the \*Ar* was released in at least three or more contiguous steps where the apparent ages agreed to within 1σ of the integrated age of the plateau segment. Pseudo-plateau ages can be defined with less than 70% of the \*Ar* released and in possibly less than three contiguous steps. The errors on the \*Ar*\*\*Ar* ratio and age of the monitor and decay constant are included in the final calculation of the error margins on the pseudo-plateau ages.

The analytical data and parameters used for calculations (for example, isotopic ratios measured on potassium, calcium and chlorine pure salts; mass discrimination; atmospheric argon ratio; J parameter; decay constants) and reference sources are available in Supplementary Dataset 3.

Plate model. For our final geodynamic model, we used the global rotations and continental polygons from the Matthews GPlates model as a template. From this template, we modified the tectonic history of the BT to reflect our palaeomagnetic results. Furthermore, the positions and palaeogeography of Greater India, Indochina, the Kohistan Arc, the Lhasa Terrane, Sumatra and the Woyla Arc were configured to better reflect more recent studies. In Fig. 1b, the global reconstruction with the Greater India basin hypothesis is based on a different set of palaeogeographic reconstructions. All plate tectonic reconstructions were configured to better reflect more recent studies. A detailed discussion on the choice for this reference frame.

Data availability

The authors declare that all data supporting the findings of this study are available within the main article, its Supplementary Information, Supplementary Dataset 1 (palaeomagnetic mean directions), Supplementary Dataset 2 (palaeomagnetic data per sample) and Supplementary Dataset 3 (\*Ar\*\*Ar* data and parameters).

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