

Tectonic history of East Asia and the Asiana hypothesis

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Abstract

When almost all continents were assembled in the late Paleozoic supercontinent Pangea, East Asian continental blocks existed as distinct, separate entities. Ocean closures and stepwise assembly of these blocks into larger continents were the main paleogeographic changes to influence paleoclimate and biogeography during Pangea time. In this Perspective, we review how Triassic assembly of the East Asian blocks formed the only major continent, the size of South America, that was never part of Pangea: we name this continent Asiana. To quantify its paleogeography, we computed site-level based paleolatitude paths based on an up-to-date paleomagnetic database. Asiana formed in the Northern Hemisphere (sub)tropics, bounded in the south by the Mesotethys and in the north and west by the Mongol-Okhotsk-Waser ocean. Asiana then traveled 2000-3000 km towards 'Eurussia' in the early Cretaceous, forming Eurasia. Puzzlingly, absence of a widespread geological record of intracontinental shortening suggests that this convergence closed the Mongol-Okhotsk-Waser ocean at a sparsely identified suture, yet Asiana dinosaurs suggest that transient Triassic and Jurassic land bridges must have existed: their locations remain unconstrained. Subduction remains of Asiana's assembly and evolution are seismically imaged as the deep-mantle 'slab graveyard' below Asia. The Asiana hypothesis affects paleoceanography and paleoclimate, biogeography, and geodynamics, and requires field mapping to unravel its approach to and collision with Eurussia.

1. Introduction

Paleogeographic reconstructions show the distribution of the evolving oceans and continents relative to the equator and pole, and they form the basis for interpretation of geodynamics, paleoclimate, paleoceanography, and biogeography¹. Most modern continents were once part of the late Paleozoic-early Mesozoic supercontinent Pangea^{1,2}, but the crust underlying modern East Asia was not². The continental fragments of East Asia (Fig. 1) were separated from southern Pangea (Gondwana) by the Tethyan oceans, and from northern Pangea (Laurasia) by Asian ocean basins^{3,4}. Their tectonic motions were the most prominent paleogeographic changes that influenced paleoceanographic, climatic, and biogeographic shifts in Pangea times². One complicating factor in these paleogeographic studies is that the ocean basins between the continents have all since subducted. Thus, interpretation of their plate tectonic history relies entirely on paleomagnetic data and sparse geological records. The incompleteness of the geological record means that the east Asian continental reconstructions vary widely in how the thousands of kilometers of paleomagnetically demonstrated convergence between them was accommodated by oceanic subduction and intracontinental shortening¹⁻⁹.

Paleomagnetism studies the Earth's magnetic field recorded in rocks^{10,11}, and quantifies paleogeography through the angle of the magnetic field relative to horizontal (i.e., inclination) that quantifies paleolatitude, and the angle with north (i.e., declination) that quantifies vertical axis rotation. Paleomagnetic data constrain divergence during ocean basin opening and convergence during their closure, as well as large-scale intraplate deformation of continents¹². For the East Asian continental blocks, paleomagnetic data indicate that tectonic motions in the late Paleozoic and Mesozoic were thousands of kilometers larger than accounted for in incomplete geological records^{8,9,13-15}. The paleogeographic interpretation of this discrepancy has major implications for the presence and connectivity of ocean basins to the east of Pangea for much of the Mesozoic, strongly impacting the interpretations built on paleogeography.

Recent analyses showed that a key source of paleogeographic uncertainty stems from classical ways of paleomagnetic data treatment, in which data uncertainty was not

propagated^{16,17}. Statistical procedures have therefore been developed to propagate uncertainty due to artifact correction associated with compaction of sedimentary rock, uncertainty in rock age, measurement error, and paleomagnetic field behavior¹⁸⁻²¹ into the final reconstructions¹⁶. These have recently been applied to place the global mosaic of Pangea-based continents in their paleogeographic position at unprecedented precision²², but will here for the first time be applied to the Asian continental tectonic history.

In this perspective, we compile all available paleomagnetic data constraining the Permian to Cretaceous paleogeographic history of East Asian continents and evaluate their reliability following recent standards (Box 1). We summarize geological data that outline original continental fragments and the intervening suture zones, as well as information about the oceans that closed to form these zones. We develop paleolatitude curves of the evolving East Asian continent, present a new paleogeographic reconstruction of Tethyan and Asian ocean histories, and illustrate where the lost lithosphere predicted by our reconstruction is in the mantle below East Asia using seismic tomography. We conclude by discussing some of the implications for paleoclimate, environment, oceanography, paleobiogeography, and geodynamics, and outline how field geological and paleomagnetic studies may further illuminate the complex amalgamation of eastern Eurasia.



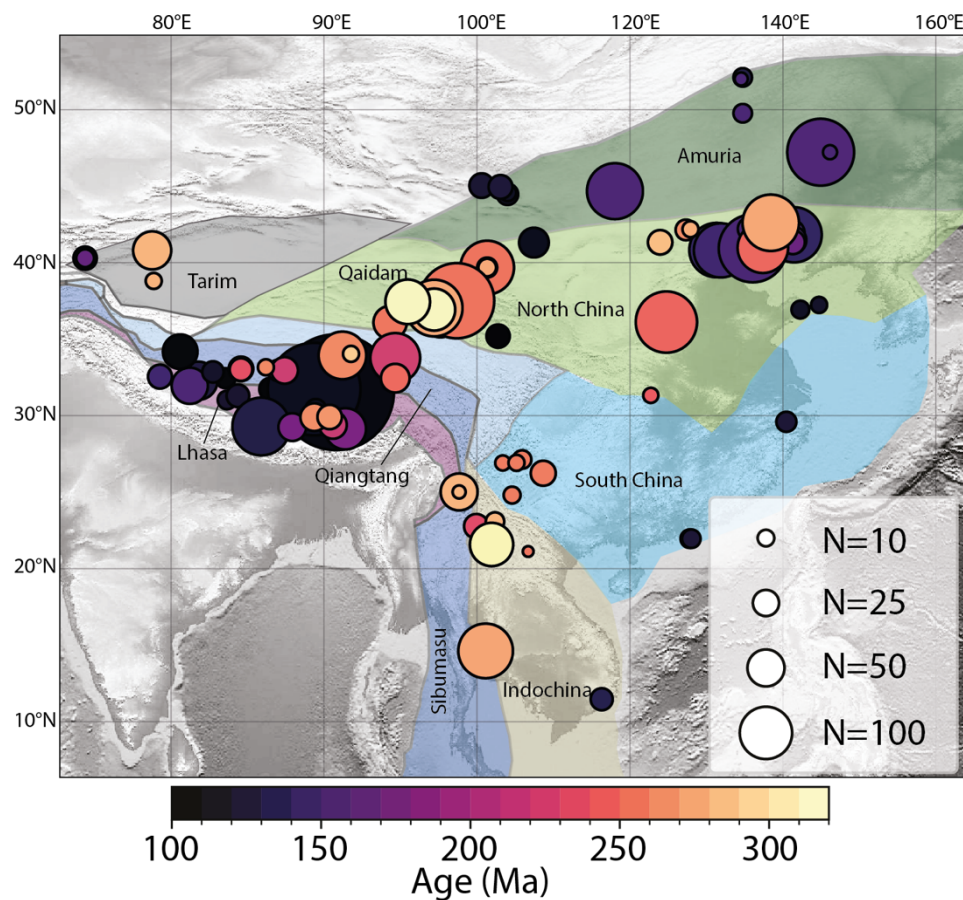
Fig. 1. Tectonic map of Asia, outlining the main Asiana-related continental fragments, between Eurasia-Siberia in the northwest, India in the southwest, and plates of the Pacific

ocean in the east. M-O: Mongol-Okhotsk suture; SO: Solonker suture; QDS: Qinling-Dabie suture; S-G: Songpan-Ganzi; AL-MJ: Ailao Shan-Majiang suture; CN-ML: Changning-Menglian suture; SS: Shan Scarp; IYT: Indus-Yarlung Tsangpo suture; BG-NJ: Bangong-Nujiang suture; ATF: Altyn Tagh fault; RP: Rushan Pshart suture; WA: Waser suture; SI: Sistan suture.

Box 1 | Paleomagnetic database of East Asian continental blocks

To compute paleolatitude paths for the tectonic blocks of Asia and quantify the paleogeographic evolution of oceans and continents east of Pangea during amalgamation of Eurasia, we compiled a paleomagnetic database for the main continental blocks of East Asia (Box Fig. 1). For each dataset, we compiled age and uncertainty, mean direction and pole, and statistical parameters including the 95% confidence (A_{95}) and Fisher²³ precision parameter (K).

We follow the same criteria for inclusion in the database as that applied to the database used for the latest global apparent polar wander path that serves as the reference²²: (i) All datasets were interpreted by the original authors to represent primary spot readings of the paleomagnetic field; (ii) we included only data with statistical properties that may be explained by paleosecular variation of the magnetic field alone¹⁴ and (iii) with more than four spot readings ($N > 4$); (v) For sedimentary rocks, we included only data corrected for compaction-induced inclination shallowing that typically leads to systematic underestimation of paleolatitude, using the E/I (with $N > 80$ ^{19,20}) or SVEI test¹⁸. Most paleomagnetic studies of sedimentary rock reported only mean directions and statistical parameters. Without individual sample-level directions, it is not possible to correct these for inclination shallowing. Such datasets are retained in the database and plotted in the figures but are not used in the computation of paleolatitude reference curves. The curated reference database is archived at the Reference Database Portal at APWP-online.org²⁴, and version 1.0 is available in the Supplementary Data (Box Fig. 1).



Box Fig 1. Paleomagnetic sampling locations and collection size of the datasets that provide reliable information for paleogeographic interpretation, from the curated Paleomagnetic Database for East Asian continental blocks. Color reflects age, dot size represents the number of paleomagnetic spot readings in each collection.

/Box 1

2. 300-200 Ma Continental assembly of Asiana

Reconstructions of the major continents have long revealed how the supercontinent Pangea formed in late Devonian to Carboniferous time when Gondwana, collided with Laurussia²⁵. Pangea grew when the Siberian craton, surrounded by the Central Asian Orogenic Belt that formed by Paleozoic accretion from subducting paleo-Asian oceans^{26,27}, collided with eastern Baltica to form the Urals in late Permian time²⁸. The Tarim continent also collided with the Central Asian Orogenic Belt, forming a late Permian suture in the Tien Shan mountains²⁹.

Against this framework, we summarize the main continents of East Asia, and their motions since the Permian as revealed by paleolatitude paths that we computed based on the paleomagnetic database of East Asian blocks (Box 1, 2; Fig. 2).

2.1 East Asian continents, sutures, and paleolatitude

Amuria is the northernmost of the East Asian blocks (Fig. 1). Its crust is part of the Paleozoic Central Asian Orogenic Belt, but it is separated from Siberia by the Mongol-Okhotsk suture zone that is thought to be much younger, late Jurassic or earliest Cretaceous in age. This hypothesis stems from Triassic and Jurassic magmatic arc rocks found on both sides of the Mongol-Okhotsk suture³⁰⁻³³ and from paleomagnetic data (Fig. 2C) that robustly show that Amuria together with the China blocks, converged with Siberia until the early Cretaceous^{6,9,34-36}. The Mongol-Okhotsk ocean is therefore thought to have opened within the Central Asian Orogenic Belt, breaking 'Amuria' from Siberia in Permian time^{34,37} (Fig. 3A). However, a deep-marine Mesozoic accretionary oceanic record is not known from the Mongol-Okhotsk suture^{38,39} – magmatic geochemistry from the adjacent arcs suggests that thick sedimentary sequences were subducted³³. The Paleozoic structure of the Central Asian Orogenic Belt defines a westward convex orocline with the mapped Mongol-Okhotsk suture in the center²⁶ (Fig. 1). This has led to the hypothesis that this orocline formed by Jurassic-early Cretaceous Mongol-Okhotsk closure^{6,9,40}, although this hypothesis leads to space problems farther south, as discussed below.

Amuria is bounded to the south by the early Triassic Solonker suture from the North China block⁵, which also includes the Alxa block⁴¹, the Paleozoic Qilian Shan orogen and the Qaidam block⁴² (Fig 1). These blocks were together part of Paleozoic Gondwana¹⁴ and broke off as a coherent continent in Devonian time^{43,44}. There are insufficient paleomagnetic data from Amuria to quantify its convergence and collision history with North China, and reconstruction of its motion history relies on the estimated age of the Solonker suture, and the North China paleolatitude path (Fig. 2C).

The North China block is bounded to the south by the Qinling-Dabie suture from the South China block (Fig. 1). This block comprises a Precambrian craton and an early Paleozoic

accretionary orogen that also rifted from Gondwana in the Devonian^{45,46}. During this break-up, the Paleotethys ocean basin formed between China blocks and the Gondwana Margin. In Carboniferous to Permian time, the North and South China blocks were separated and a branch of the Paleotethys ocean formed in between⁴⁷. The closure of this Paleotethys branch forming the Qinling-Dabie suture occurred in Triassic time, leading to deep tectonic burial of the northern South China margin below North China around 245-235 Ma⁴⁸⁻⁵¹. Reliable paleomagnetic data from South China are sparse, as most legacy datasets suffer from unresolved inclination shallowing (Supplementary Data), and because the original data are unavailable, no ad hoc corrections can be made. However, data from the Emeishan large igneous province reveal $\sim 15^\circ$ (~ 1600 km) of paleolatitudinal convergence between the North and South China blocks from ~ 260 Ma until Triassic collision. Subsequently, this margin was exhumed in the Dabie Shan around 210-190 Ma^{52,53}, while N-S convergence occurred at the western continuation of the suture in the Qinling orogen, associated with a clockwise rotation of South China relative to North China^{47,51,53,54}. Since the conclusion of significant motion at the Qinling-Dabie suture in the Triassic, the China blocks have been part of the same plate and continent^{47,54}. Paleomagnetic data from both blocks reveal that after the Triassic, the China Blocks, including Qaidam, and together with Amuria, underwent 2000-3000 km of convergence with Eurasia, increasing eastwards, until early Cretaceous time.

The South China block is bounded to the south from the Indochina block by the middle Triassic (~ 230 Ma) Aliao Shan-Majiang suture^{7,55,56} (Fig. 1). To the southwest, the Indochina block is bounded by the middle Triassic Changning-Menglian Suture from Sibumasu⁵⁷ (Fig. 1). The Changning-Menglian ocean basin was likely narrow, such that collisions of Sibumasu, Indochina, and South China occurred within a short time span⁷. The Indochina block may originally have occupied the eastern part of the Tibetan Plateau, but it was extruded ~ 600 -700 km south-eastwards by Cenozoic strike-slip faults to its present-day position^{58,59}. The Sibumasu terrane, however, was part of a much wider ribbon continent that continued north-westwards throughout the Tibetan Plateau, where it is known as the Qiangtang block, then westwards as the Southern Pamir-Karakoram block^{60,61}, and into Afghanistan as the Helmand block^{62,63}. The Qiangtang-Sibumasu-Helmand and Indochina blocks derived from northern Gondwana, breaking off in Permian time, and their northward motion closed the

200 Paleotethys in the north and opening the Mesotethys in the south^{7,60,61}. Possibly, the
201 Qiangtang block broke into two fragments (North and South Qiangtang) separated by an
202 ocean basin^{64,65} although alternative geological explanations invoke a single block⁶¹.
203 Arguments for a wide separation between these come from different Permian warm vs cold-
204 water flora and fauna⁶⁶. Our paleomagnetic database shows no difference between North
205 and South Qiangtang paleolatitudes in Triassic and younger times, and if a basin still existed
206 then, it was likely narrow, as between Sibumasu and Indochina (Fig. 2C).

207 The Paleotethys in Tibet sutured in the late Triassic, 10-20 Myr after the closure of the
208 Aliao Shan-Majiang and Changning-Menglian sutures and formed the Songpan Ganzi
209 accretionary complex between Qiangtang in the south, Qaidam in the North, and South
210 China in the east^{61,67} (Fig. 1). Most paleomagnetic data come from the Qiangtang portion of
211 the ribbon, which reveals high paleolatitudinal motion rates of 60° between 260 and 230
212 Ma, i.e., >20 cm/yr, followed by slower convergence with the Asian blocks until ~200 Ma,
213 when subduction in the Songpan Ganzi complex stopped (Fig. 2D). Paleomagnetic data from
214 Indochina and Sibumasu are sparser but are consistent with this history. Like the North and
215 South China blocks, the paleomagnetic data from Qiangtang reveal up to 3000 km of post-
216 Triassic convergence with Eurasia.

217 To the west, the East Asian continental blocks are separated from Eurasian continental
218 units by major fault zones. The Helmand block and Southern Pamir-Karakoram portions of
219 the larger Sibumasu-Qiangtang-Helmand ribbon continent are not juxtaposed against East
220 Asian blocks, but against blocks that were part of Eurasia in the late Triassic, known as the
221 Iranian Cimmerides⁶². These Iranian Cimmerides evolved to the west of the East Asian
222 Tethyan system, in a simpler plate tectonic system: in the Iranian Tethyan segment, a single
223 continental ribbon continent broke off the Arabian margin of Gondwana in the Permian and
224 collided with the northern Tethyan margin in the late Triassic^{68,69}, closing the Paleotethys
225 and opening the Neotethys^{70,71}. The boundary between the Helmand and Southern Pamir-
226 Karakoram zone and Eurasia is the Early Cretaceous Waser suture that has a subduction
227 record since the Triassic⁷². The Waser Suture may be traced into the Pamir region along the
228 northern boundary of the Southern Pamir-Karakoram zone in Rushan Pshart suture⁷³. This
229 shows that while Sibumasu-Qiangtang-Helmand had connected to the China blocks in the

late Triassic, it remained separated by a subduction zone from Eurasia until the Early Cretaceous. To the northeast, the Qaidam block, which moved together with North China since the Devonian^{13,14,74}, is separated from the Tarim block by the Altyn Tagh fault zone. This fault zone has an estimated Cenozoic displacement of ~400 km^{75,76}, but is suspected to be a reactivated suture zone between Tarim and Qaidam, which have different paleogeographic histories⁷⁷. Paleomagnetic data show >2000 km of convergence between the Tarim and Qaidam blocks since the Permian, consistent with the convergence history between the China blocks and Eurasia (Fig. 2B, C). This suggests that this suture zone may form a link between the Waser suture of Afghanistan with the Mongol-Okhotsk Suture of Mongolia^{13,14}. However, no geological record of this suture zone has so far been found and it may be buried below the Tarim basin¹³.

To the south, the Qiangtang block is separated from the Lhasa block by the Early Cretaceous Bangong-Nujiang suture^{60,61,78}. The Lhasa block separated from Gondwana during or before the Triassic^{79,80}, opening the Neotethys ocean. Paleomagnetic data from Lhasa reveal a northward drift at rates of up to 10 cm/yr in Middle Jurassic to Early Cretaceous time (Fig 2D). Data from Lower Permian to Upper Jurassic rocks of Lhasa all reveal an identical paleolatitude of ~15°S, even though the major continents reveal significant paleolatitudinal change, likely because of true polar wander⁸¹. This apparent paleolatitudinal standstill may indicate regional remagnetization of the Lhasa block between the late Triassic and middle Jurassic (Fig. 2D). Final closure of the Neotethys led to the youngest collisions in the amalgamation of the east Asian continent: continental fragments of Argoland, a microcontinental archipelago that rifted off west and northwest Australia in the Jurassic, collided with SE Asia in the late Cretaceous to Eocene^{82,83} and continental crust of the Indian plate collided with Eurasia in the Cenozoic⁸⁴, forming the Himalaya.

Box 2 | Reconstructing paleogeography with paleomagnetism

Paleomagnetic poles

Paleomagnetic data record directions of the Earth's past magnetic field preserved in rocks. Assuming the long-term (~10⁴-10⁶ years) magnetic field approximates a geocentric axial dipole

(GAD), magnetic inclination is a simple function of latitude, and declination records vertical axis rotation. Paleomagnetism thus constrains paleolatitude and azimuthal orientation of plates and continental fragments. The paleomagnetic direction in each location on a plate varies with its paleolatitudinal position, but for a given age, all paleomagnetic directions of a plate point to the same paleomagnetic pole. Converting paleomagnetic directions into poles therefore allows combining data from across plates and continents and show how the paleomagnetic pole wandered relative to the plate (apparent polar wander paths, APWPs). Such compilations underpin regional and global reconstructions of plate motions relative to the pole (and spin axis), quantifying paleolatitudinal motions and vertical axis rotations during ocean basin opening and closure, continental collisions, and intraplate deformation.

Paleomagnetic pitfalls

Paleomagnetic records have biases, errors, and uncertainties. The main challenge is recovering a primary magnetization acquired during rock formation. This requires recognition and removal of secondary remagnetization that overprint the original signal. Incomplete removal biases directions and paleogeographic reconstructions. In sedimentary rocks, compaction may cause inclination shallowing, thus underestimating paleolatitude. Magnetization age uncertainty, uncertain structural corrections, and under-sampling of secular variation of the paleomagnetic field are other key error sources. The paleomagnetic community therefore developed and regularly updates reliability criteria to determine which legacy data meet modern standards (see Box 1).

Embracing uncertainty

Paleomagnetic reference curves have been developed for decades based on combining paleomagnetic poles, both for global reconstructions^{12,85} and for east Asian continental blocks^{6,9}. These showed polar wander that supported paleogeography interpretations, but did not propagate data uncertainty in age, position, or collection size. This was shown to be the source of major confusion and differences in interpretation of paleomagnetic data^{16,17}. Recent approaches therefore updated polar wander computation, focusing on propagating key uncertainties in age, inclination shallowing magnitude, and dispersion of site-level data^{16,86,87}.

A site-based approach has also been used to compute a global APWP that provides an absolute reference frame relative to the spin axis for the global plate reconstruction²², using a statistical re-sampling approach to propagate uncertainties related to data dispersion, age, and inclination shallowing into the final polar wander estimate (see Supplementary Methods). In this paper, we provide the first such an analysis for the East Asian continental blocks.

Reconstructing paleolatitude through time

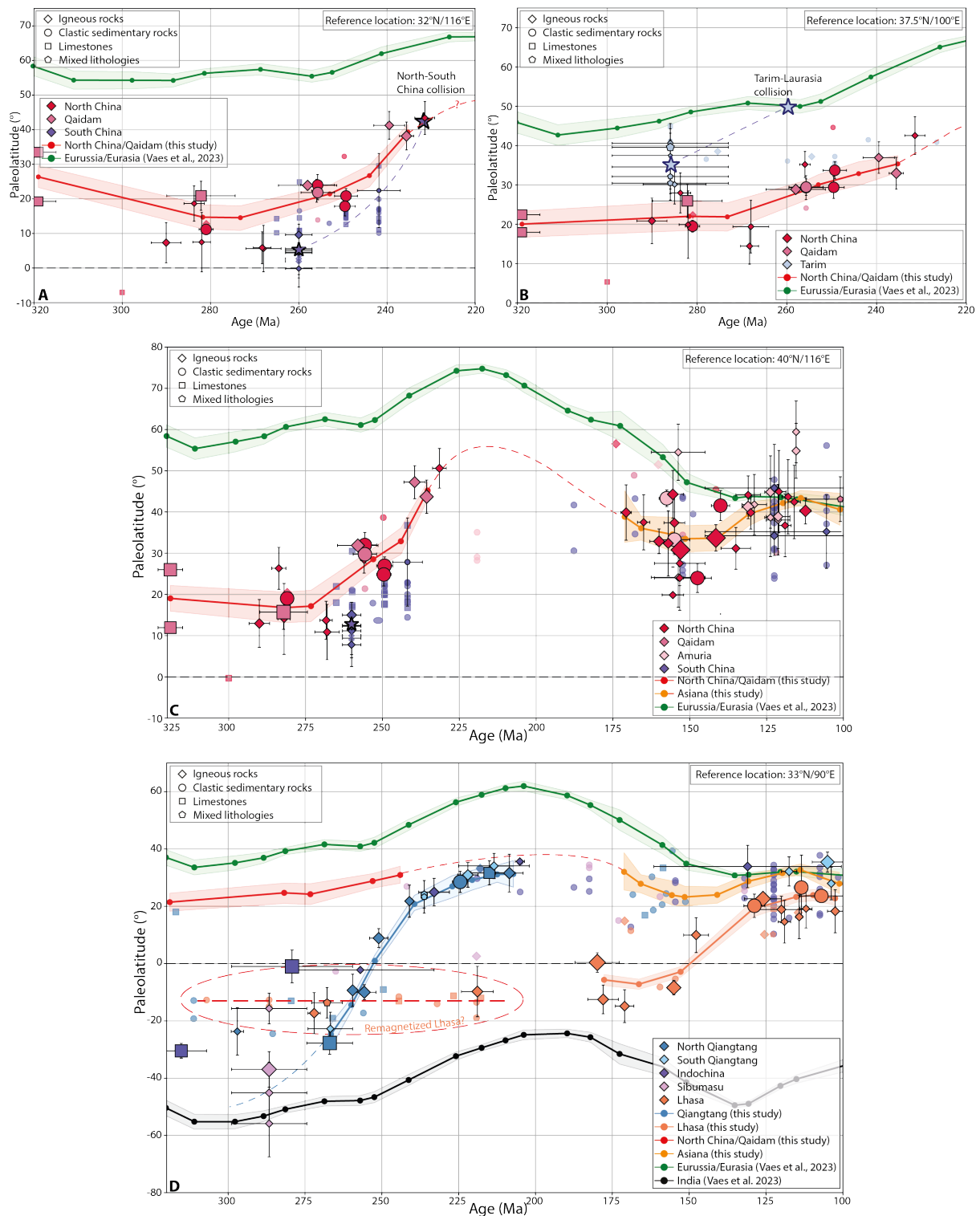
The paleolatitude history of tectonic plates and continents can directly be derived from APWPs. However, local vertical-axis rotations due to tectonic deformation can strongly affect individual pole positions and bias reference poles. Because of widespread deformation of the East Asian continental blocks, such rotations form a problem for polar wander computation. Traditionally, paleolatitude evolution of Asian terranes was analyzed by projecting study-mean paleomagnetic poles (or: paleopoles) from a tectonic block onto small circles centered on a reference location⁸⁸. This provided a mean paleolatitude and confidence region. However, it does not propagate uncertainties in age and position of study-mean poles, or the size of the underlying datasets. Here, we compute site level-based paleolatitude-only paths for the East Asian continental blocks that allows incorporating these uncertainties (Supplementary Methods).

/Box 2

[2.2 Reconstructing the assembly of Asiana](#)

The geological constraints from the Asian suture zones (Fig. 1) combined with the available paleomagnetic constraints (Fig. 2) show that during Permian time, the East Asian continental blocks were still dispersed over multiple tectonic plates and separated by oceans. North and South China plates existed around the equator and northern hemisphere (sub)tropics, respectively, and they were separated from a plate to the south that carried the Sibumasu-Qiangtang-Helmand and Indochina blocks (Fig. 3). We did not attempt a full plate tectonic reconstruction, and it is possible that intra-oceanic subduction zones and fully oceanic plates existed within these oceans. However, at a minimum, three plates must have existed to the

318 east of Pangea, carrying Amuria, North China-Alxa-Qaidam-Qilian Shan, and South China
 319 (Fig. 3).



320
 321 Fig. 2A) Paleolatitude paths for North China-Qaidam in Permian to early Triassic time, in red,
 322 for a reference location on the Dabie suture zone. At ~260 Ma, South China is ~15° of latitude
 323 to the south. Geological data indicate collision is underway in early Triassic time⁴⁸⁻⁵⁰. B)

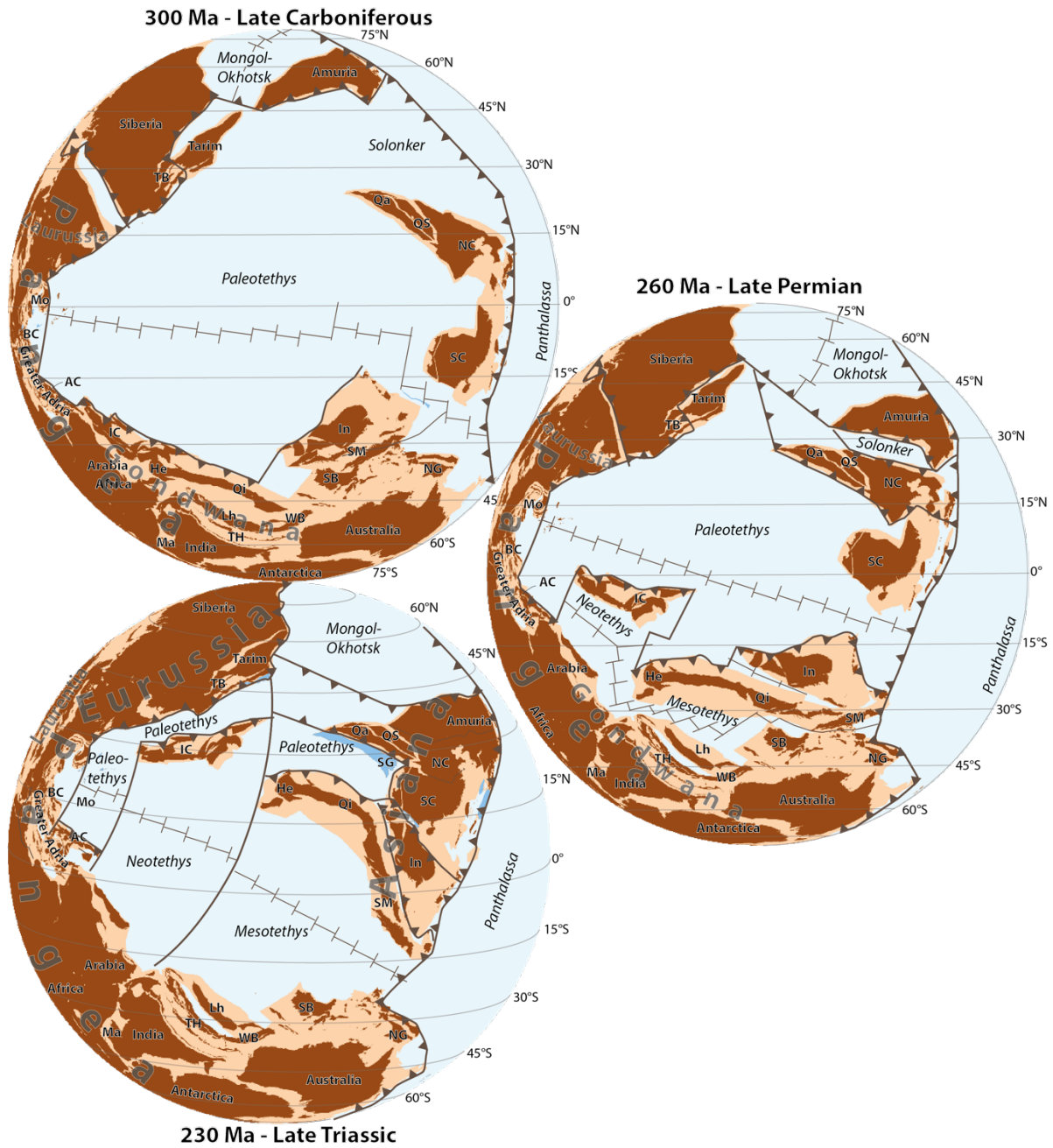
Paleolatitude path of North China-Qaidam for a position in the Qaidam block. At ~285 Ma, Tarim is separated by ~10° from Eurasia. Geological data indicate collision in the Tien Shan suture in the late Permian²⁹. C) Paleolatitude path of North China-Qaidam in Permian to early Triassic time, and of Asiana in late Jurassic-early Cretaceous time for a reference location in North China. Asiana's paleolatitude between ~250 and 180 Ma remains poorly constrained due to a large data gap. Net paleolatitudinal Asiana-Eurussia convergence in this interval is ~10° (~1000 km). Paleomagnetic data show Asiana-Eurasia convergence continued until ~130 Ma. D) Paleolatitude path of Qiangtang and Lhasa relative to North China-Qaidam, Asiana, Eurasia and India. Qiangtang migrated at a high paleolatitudinal rate of 60°/30 Myr between 260 and 230 Ma (~20 cm/yr) northward in late Permian to Triassic time, until collision with Qaidam/Asiana in late Triassic time. Paleomagnetic data of North and South Qiangtang show no paleolatitudinal difference. Lhasa moved northward until the Early Cretaceous and collided with Asiana around the same time as Asiana's collision with Eurussia, forming Eurasia. All Lhasa paleolatitude data from Permian and Triassic time (dashed ellipse in Fig. 2D) give the same southern hemisphere tropical paleolatitude. This may suggest regional pervasive remagnetization between late Triassic and mid-Jurassic time.

Amuria was separated by the Mongol-Okhotsk back-arc basin to the north³⁷. It collided and merged with North China upon closure of the Solonker ocean in the early Triassic⁵, following dominantly N-S relative convergence⁴³ (Fig. 3). Not long after this collision, South China collided with North China at the Qinling-Dabie suture. Most authors suggest that the convergence between North and South China associated with closure of the intervening branch of the Paleotethys was mostly N-S convergent and accompanied by clockwise rotation of South China relative to North China^{89,90}, a view we follow here (Fig. 3). However, paleomagnetism cannot constrain a paleolongitudinal component of motion, and an alternative hypothesis that correlates the Emeishan large igneous province to deep-mantle structure invokes a westward motion component of 1000s of km of the South China block^{2,91}.

Prior to their Triassic collision, Sibumasu and Indochina were separated by an oceanic branch, and possibly the Qiangtang terrane also comprised two blocks. However, because

paleomagnetic data reveal no significant paleolatitudinal relative motions between these blocks, and the collision of Sibumasu with Indochina is almost simultaneous with the Indochina-South China collision⁷, we consider that these blocks and narrow oceans formed part of the same plate. A modern equivalent may be Zealandia, to the east of Australia⁹², which contains several continental fragments bounded by narrow deep basins, separated by the Tasmanian ocean basin from eastern Australia^{93,94}. Reconstructed equivalents elsewhere are microcontinental archipelagoes such as Argoland⁸² that broke off NW Australia and is now part of the SE Asian accretionary orogen, or Greater Adria that broke off north Africa and is now part of the Mediterranean accretionary orogen⁹⁵ (Fig. 3). These examples show stretched continental domains, often largely covered by shallow seas, with intervening narrow, deep, in part oceanic basins that formed during multiphase extension of the Gondwana margin. These migrated in unison on a single plate to the northern margin of the Neotethys, after which their collision and accordion-style shortening developed multiple short-lived sutures surrounded by the main sutures of the surrounding oceans.

The closures of the Solonker ocean and the branches of the Paleotethys ocean in a short time span of a few tens of millions of years merged all the East Asian blocks, including Amuria, North China (with Alxa, Qilian Shan, Qaidam-Kunlun), South China, Indochina, Sibumasu-Qiangtang-Helmand) and the intervening sutures into a single, much larger continent (Fig. 3). This continent has been conceptually shown before on maps, but has not previously been named—instead, the literature tends to discuss the geological history of its component blocks. This major East Asian continent was roughly triangular, 7000 x 5500 x 6500 km, with an area comparable to present-day South America. Because of its size and its paleogeographic, geodynamic, and likely paleoclimatic and biogeographic importance—it was the only major continent that was never part of Pangea—we argue that it deserves its own name. We here refer to it as 'Asiana', from its birth in the Triassic. Based on the paleomagnetic evidence (Fig. 2), we hypothesize that Asiana formed part of a tectonic plate that remained independent from the rest of Eurasia from its birth in the Triassic until its merger with Eurasia in the earliest Cretaceous.



382 **230 Ma - Late Triassic**

383 Fig. 3. Paleogeographic evolution of Asiana. Update of the global Utrecht Paleogeography

384 Model⁹⁶ to version 1.1, with the blocks of Asia(na) modified according to the paleomagnetic

385 data compiled in this paper, and with subduction polarity and plate boundary interpretations

386 of the Tethyan and western Panthalassa realm based on previous plate tectonic

387 reconstructions^{7,62,66,82,95,97}. GPlates⁹⁸ rotation files are provided in the Supplementary

388 Information. Key to abbreviations: AC = Anatolian Cimmerides; BC = Balkan Cimmerides; He

389 = Helmand block; IC = Iranian Cimmerides; In = Indochina; Lh = Lhasa block; Ma =

390 Madagascar; Mo = Moesian platform; NC = North China block; NG = New Guinea; Qa =

391 Qaidam block; Qi = Qiangtang block; QS = Qilian Shan; SB = Southwest Borneo block; SC =
392 South China block; SG = Songpan Ganzi; SM = Sibumasu; TB = Tadjik basin; TH = Tibetan
393 Himalaya; Wa = Waser suture; WB = West Burma block

394

395 3. 200-130 Ma Changing ocean basins

396 The paleomagnetic data show that after its formation, Asiana must have been surrounded by
397 oceanic basins: the Mongol-Okhotsk-Waser ocean to the northwest, the Mesotethys ocean to
398 the south, and the Panthalassa ocean to the east. Its overall isolation likely had important
399 effects on paleoclimate and biogeography, and raises the question of the development or
400 breakup of possible land bridges to Eurussia to the west (see Box 3) or Gondwana to the south,
401 which we discuss in this section.

402

403 3.1 The Asiana conundrum and the Mongol-Okhotsk-Waser ocean

404 In the paleomagnetic reference frame, relevant for climate and biogeography, much of
405 the Asiana-Eurussia convergence resulted from Triassic to late Jurassic southward motion of
406 $\sim 20^\circ$ of eastern Eurussia, while Asiana slowly moved northward from ~ 20 to $\sim 30^\circ\text{N}$ (Fig. 4).
407 This interval is characterized by slow true polar wander, i.e. the tilt of the solid Earth relative
408 to the spin axis because of changes in its moment of inertia^{12,81,99}. At the paleolongitude of
409 Asiana, this caused a southward motion of the solid Earth of $\sim 20^\circ$ ¹⁰⁰. Therefore, in the
410 mantle reference frame^{101,102}, relevant for geodynamics, Asiana moved northward relative to
411 a nearly latitude-stationary Eurussia. Puzzlingly, a total of 2000-3000 km of convergence,
412 from west to east, must have been accommodated somewhere between Asiana and
413 Eurussia, but there are no known geological records of widespread Mesozoic
414 intracontinental shortening or subducted Mesozoic oceans along most of the inferred
415 Asiana-Eurussia suture zone. Solving this problem has major implications for
416 paleogeography, -climate, -oceanography, and biogeography, as well as geodynamics, but it
417 is not straightforward.

418 The Asiana hypothesis thus introduces a conundrum: how and where was Asiana-
419 Eurussia convergence accommodated, and how did this affect paleogeography? Current

reconstructions that place Asiana at the correct latitude assume thousands of kilometers of continental shortening within Asiana^{8,9}, but intracontinental shortening always leaves spectacular orogenic records¹⁰³. For example, shortening in the majestic Cenozoic Tibetan Plateau 'only' accommodated ~1000 km^{76,104} of shortening, in the Andes, 400 km or less^{105,106}, and in the >7 km high Cenozoic Tien Shan orogen, <200 km^{76,107,108}. There is no record of major Mesozoic intraplate orogenesis in Asiana.

The bulk of Asiana-Eurussia convergence must therefore have been accommodated by subduction, but only scarce records of subduction are known from the Asiana-Eurussia plate boundary: the Waser suture of Afghanistan and the western Rushan Pshart suture of the western Pamir contain sparsely described records of oceanic subduction until the early Cretaceous^{72,73}, and the Mongol-Okhotsk suture zone is flanked by Triassic and Jurassic magmatic rocks interpreted as volcanic arcs³⁰⁻³³. However, there is no geological record of accreted Mesozoic oceanic floor sediments or volcanics in the Mongol-Okhotsk suture zone^{38,39} and even though the Altyn Tagh fault between the Tarim and Qaidam blocks is commonly viewed to reactivate a suture⁷⁷, there is no known record of oceanic subduction in the region connecting the Mongol-Okhotsk and Waser sutures either.

The reconstruction of Asiana-Eurussia convergence thus does not face the challenge of interpreting a documented geological record, but to explain the absence of one. The documented convergence requires that lithosphere was subducted, and the absence of a geological record requires that all that lithosphere subducted without accretion. Such tectonic behavior is well-known from oceanic subduction – it is the default mode of subduction around the Pacific since the Mesozoic^{103,109}. Continental subduction, on the other hand, tends to leave an accretionary orogen, comprising nappes of passive margin sediments and occasionally the underlying basement^{110,111} – in fact, the cornerstone paradigm of paleogeographic reconstruction is that continental crust does not subduct without leaving a geological record that is proportional to the subducted area¹⁰³. Key examples of such continental subduction-related accretionary orogens are the Himalaya¹¹², the Alps¹¹³, and the central and eastern Mediterranean region^{95,114}. The absence of such a record along the Asiana-Eurussia boundary argues against a continental subduction scenario.

Moreover, oceanic sutures are typically narrow zones of deformation. For instance, the Indus-Yarlung suture zone in the India-Asia collision zone is rarely wider than ~ 10 km¹¹⁵. Such narrow zones may be hidden in the geological record, because of sedimentary coverage, as proposed to explain the absence of exposure of a long-suspected⁷⁷ Qaidam-Tarim suture^{13,15}. Alternatively, they could be covered by backthrusting of lower-plate rocks over the suture, such as the Great Counter thrust that locally hides the Indus-Yarlung suture zone below Tibetan Himalayan rocks¹¹⁶. A similar debate about ‘missing’ shortening exists in the Himalaya, where up to 3000 km of Cenozoic India-Asia convergence is unaccounted for¹¹⁷. There, Miocene out-of-sequence thrusting in the Greater Himalaya units may explain how a hypothetical accretionary record of Eocene-Oligocene oceanic subduction could have been removed from the geological record¹¹⁸. Conversely, it is unlikely that such processes could hide Himalaya-style accretionary orogens derived from subducted continental crust.

It may therefore be tempting to hypothesize that a contiguous Mongol-Okhotsk-Waser ocean separated Asiana from Eurussia until the late Jurassic-early Cretaceous¹³, as we portray in our reconstructions of the Asiana hypothesis (Figs. 3 and 4). The trace of this suture has been speculated to have followed the Tarim-Qaidam boundary^{13,14}, a hypothesis followed here, or the Tarim-Eurasia boundary in the Tien Shan^{51,119}. The first documented connection of Asiana with Eurussia occurred in modern northeast Iran and western Afghanistan, where the cessation of arc magmatism in the Lut block that is part of the Iranian Cimmerides around 160-150 Ma likely signals the collision with the Helmand block that formed the southwestern tip of Asiana⁶². To the northeast of this collision, the Waser suture continued closing until the early Cretaceous, whereas to the south, the Sistan ocean of eastern Iran opened between Helmand and Lut. These two processes connected in a rotation pole at the northwestern tip of the Helmand block since latest Jurassic time⁶², which is consistent with an Asiana-Eurussia rotation pole. Thus, the Asiana hypothesis predicts a first continental connection of Asiana to Laurussia, while oceanic subduction continued until the early Cretaceous from the Waser to the Mongol-Okhotsk ocean (Fig. 4).

Evidence from the dinosaur fossil record of Asiana, however, requires a more complex paleogeographic history. Our reconstruction implies that Asiana remained terrestrially isolated from its assembly in the late Triassic until the late Jurassic, ~ 160 Ma ago. While this

isolation is partly corroborated by the strong endemism seen in East Asian Jurassic vertebrate assemblages^{120,121}, it raises new questions about the assembly of the Asiana Mesozoic fauna. Indeed, sauropods are present on Asiana since at least the earliest Jurassic¹²² (200-180 Ma), and large-bodied theropods since the middle Jurassic¹²³. The presence of these massive animals inevitably requires intermittent – or permanent – land connections with Eurussia well before the establishment of the Helmand-Lut land bridge.

Such a land bridge requires even more speculative paleogeographic scenarios, and we only discuss two end-member scenarios intended to inspire future field research to unearth a more detailed paleogeography. In our scenario, an intraoceanic arc is inferred that connects the previously hypothesized subduction zone along northern Amuria⁶ with a triple junction at the Eurussian margin (Fig. 3, 4). Such intra-oceanic arcs could develop transient land bridges, as illustrated by the paleogeographic history of the Costa Rica-Panama land bridge between North and South America¹²⁴.

An alternative solution invokes a more complex scenario for the opening of the Mongol-Okhotsk ocean. Rather than a full separation of Amuria from the south Siberian margin as portrayed in our reconstructions (Fig. 3), most authors portray a scenario in which Amuria was a rotating arm that connected to Eurussia in the west. Following the Early Triassic closure of the Solonker suture between Amuria and North China, this rotation would be reversed, closing the Mongol-Okhotsk ocean. A popular hypothesis suggests the Amuria-Eurussia Euler pole was in the westward convex orocline that is defined by Paleozoic orogenic architecture to the west of the mapped Mongol-Okhotsk trace^{6,15,40,125-127} (Fig 1). Such a scenario would make a land bridge between Asiana and Eurussia throughout the Triassic to Early Cretaceous and separate the Mongol-Okhotsk ocean in the northeast from the Waser ocean to the southwest.

This oroclinal bending hypothesis introduces several kinematic complications. First, if the Eurussia-Asiana pole of rotation is in the heart of the orocline, then Asiana would have diverged from Tarim from the Early Triassic onwards, and restoring the Mongol-Okhotsk ocean closure would place Asiana on top of Eurasia in the early Triassic, which is clearly impossible. Therefore, this scenario requires that from the Triassic to early Cretaceous, a plate boundary accommodating oblique convergence should have existed between North

China and Amuria, for which there is also no documented geological record. Therefore, this scenario adds further complication and speculation that may serve as basis for targeted field study to reconcile the Asiana-Eurussia convergence history with east Asia's geological record.

Box 3 – Paleogeographic nomenclature of northern hemisphere continents

The continental landmass comprising Europe and Siberia that formed northern Pangea in Mesozoic time, and that existed until the Cenozoic opening of the North Atlantic ocean, is commonly referred to as Laurasia¹²⁸, as a hybrid of 'Laurentia' (the continent that comprised North America and Greenland) and Eurasia. However, our paleomagnetic data compilation shows that the 'Asiana' part of Eurasia still underwent ~20-30° paleolatitudinal convergence in Triassic to Early Cretaceous time before merging with Eurasia. Such major convergence (2000-3000 km) required a subduction-dominated plate boundary to close the Mongol-Okhotsk-Waser ocean in earliest Cretaceous time. The name 'Laurasia' is thus inadequate before the early Cretaceous. The more apt name 'Laurussia¹²⁹' was already used for the continent comprising Laurentia and Baltica that formed with the Ordovician Caledonian orogeny, which did not include Siberia yet because the Ural ocean only closed in Permian time. Because Laurentia already started rifting from Eurasia in the Triassic, at the location where the North Atlantic ocean would form 150 million years later¹³⁰. We refer to the continental landmass between this rift and the Mongol-Okhotsk-Waser ocean as 'Eurussia'. Eurasia finally formed when Asiana and Eurussia collided, in the early Cretaceous (Fig. 2B and 3).

/Box 3

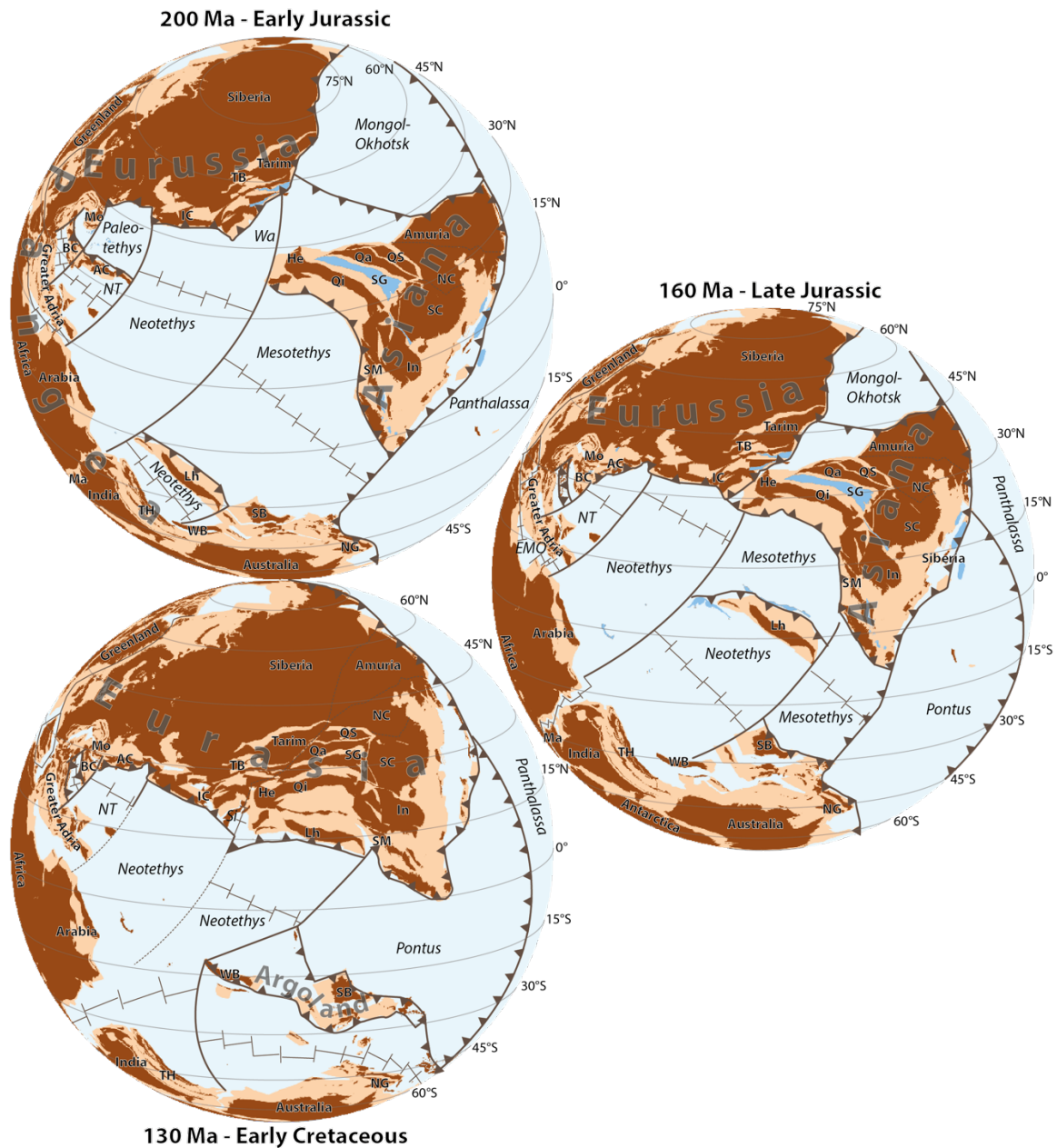


Fig. 4. Paleogeographic evolution of the paleogeographic evolution of Asiana and its merger with Eurasia. Key to abbreviations: AC = Anatolian Cimmerides; BC = Balkan Cimmerides; EMO = Eastern Mediterranean ocean; He = Helmand block; IC = Iranian Cimmerides; In = Indochina; Lh = Lhasa block; Ma = Madagascar; Mo = Moesian platform; NC = North China block; NG = New Guinea; NT = Neotethys; Si = Sistan ocean; Qa = Qaidam block; Qi = Qiangtang block; QS = Qilian Shan; SB = Southwest Borneo block; SC = South China block; SG = Songpan Ganzi; SM = Sibumasu; TB = Tadjik basin; TH = Tibetan Himalaya; Wa = Waser suture; WB = West Burma block

3.2 Evolution of the Mesotethys ocean

The Permo-Triassic Mesotethys ocean that bounded Asiana to the south was connected to the Panthalassa ocean to the east. Its mid-oceanic ridge likely ended in a triple junction with transform or subduction plate boundaries with western Panthalassa plates. To the west, the Mesotethys was bounded by transform-dominated plate boundaries from the Neotethys ocean of the Iranian segment^{62,131} (Fig. 4).

The Mesotethys started closing when the Lhasa fragment rifted from Gondwana and started its northward journey towards the southern Asiana margin. Lhasa arrived in the early Cretaceous^{60,61,78} (Fig. 2D, 4)—around the same time or shortly after Asiana's collision with Eurussia. Mesotethys closure was, like its opening, dominated by S-N motion, likely reusing the existing transform plate boundary with the Iranian Neotethys segment (Fig. 4). Our reconstruction displays a subduction zone along both the northern Lhasa margin and the southern Qiangtang margin as widely agreed upon^{61,78,80}. However, the presence of Jurassic ophiolites within the Bangong-Nujiang suture zone of Tibet, which marks the geological remains of the Mesotethys, have been used to argue that intra-oceanic subduction zones and smaller plates once occupied the oceanic basin¹³².

The paleomagnetic database for Lhasa clearly recorded part of this northward motion. The data reveal a southern hemisphere tropical paleolatitude around 10°S in the Jurassic, followed by ~20°N paleolatitudes from the early Cretaceous onwards when Lhasa had accreted to the southern Eurasian margin. During much of the Jurassic, Lhasa's northward plate motion towards Asiana coincided with a southward latitude shift of the major continents at the Asian longitude due to true polar wander. As a result, Lhasa remained near the equator throughout much of the Jurassic¹⁰⁰. The northward absolute plate motion of Lhasa likely started at the end of this phase of true polar wander in the Late Jurassic, after ~155 Ma, confirmed by a recent paleomagnetic pole at ~148 Ma indicating a paleolatitude of ~12°N¹³³.

Pre-Jurassic paleolatitudinal and plate motion of Lhasa may be more problematic to interpret from paleomagnetic data (Fig. 4). Most paleomagnetic data from Triassic and older rocks of the Lhasa block have been published in the last decade. Because the late Triassic

paleolatitude was close to the north Gondwana margin, Lhasa was interpreted to have broken off Gondwana—perhaps from the west Australian/Argoland margin⁸⁰—in the Late Triassic¹³⁴. However, the compiled paleomagnetic data for the early Permian to late Triassic paleolatitude from Lhasa, spanning 100 Myr, all return a paleolatitude of ~15°S (Fig. 2D)—suggesting widespread remagnetization. If not, then these data would require that Lhasa underwent a ~20° southward motion relative to Gondwana in this interval, which itself underwent northward paleolatitudinal drift due to true polar wander^{12,81,99} (Fig. 2D). Such a scenario would require a Permo-Triassic subduction in the Neotethys.

Lhasa's lower Permian stratigraphy contains diamictites and other glacial deposits¹³⁵. If the 15°S paleolatitudes are correct, then glaciations reached the tropics, amounting to a near-Snowball Earth world, even though at similar latitudes in the northern hemisphere, Asiana blocks did not record such conditions. Likewise, pre-270 Ma (South) Qiangtang data suggest 15°S paleolatitudes¹³⁶ despite the presence of diamictites (Fig. 2D). Widespread remagnetization of the Lhasa block may have occurred during a hypothetical late Triassic break-up from Gondwana, or post-break-up in the early Jurassic, during its northward motion towards Eurasia. (South) Qiangtang may have remagnetized upon its late Permian break-up. This option has been discussed before¹³⁷⁻¹⁴⁰: the commonly reported positive fold tests for Lhasa paleomagnetic data only show that magnetization acquired predates Cretaceous folding and do not preclude remagnetization. However, the counterargument is that the low Permian latitudes for Lhasa also come from volcanic sequences that do not easily remagnetize^{137,138} (but occasionally do¹⁴¹). In our reconstruction, we place Lhasa against the Gondwana margin, at high latitudes, during Permian glaciation. We infer a first break-up phase in the Permian following evidence for rifting of that age in the Tibetan Himalaya¹⁴², and final northward motion from the Late Triassic onwards, associated with renewed rifting of the Gondwana margin recorded in Argoland and west Australia⁸².

3.3 Oceanic gateways and paleoclimate evolution

The overwhelmingly majority of Mesozoic paleobiogeographical and climate modeling studies rely on the PALEOMAP paleogeographic reconstructions¹⁴³, in which the closure of

the Mongol-Okhotsk ocean occurred in the late Permian and Asiana and Eurussia are persistently connected. Our paleomagnetic synthesis instead shows a much lower paleolatitude for Asiana than inferred in those reconstructions and places this final closure in the early Cretaceous (Fig. 4), i.e. almost 150 million years later than commonly inferred in paleoclimate simulations.

This calls for a reassessment of Triassic and Jurassic oceanic circulation. In the conservative scenario of a continuous landbridge through Amuria, a Waser oceanic embayment would have existed north of the Tethys ocean, and a mid-to-high latitude Mongol-Okhotsk ocean connected to the Panthalassa ocean throughout the Triassic-Jurassic. In the single-suture scenario (Figs. 3, 4), a transient deepwater corridor may have existed forming a shortcut between the Tethys and Panthalassa oceans between Asiana and Eurussia. This would impact oceanography and climate in several ways. Semi-enclosed embayments may play a role in ocean circulation and deep-water formation¹⁴⁴. A transient Tethys-Panthalassa gateway could have a significant impact on global heat transport and glacial dynamics¹⁴⁵, as well as on the oxygenation of the Jurassic Neotethys, which is critical to consider when modeling Ocean Anoxic Events and Jurassic hyperthermals¹⁴⁶.

The shrinking of the Mongol-Okhotsk-Waser ocean during the Jurassic, and the establishment of the Helmand-Lut land bridge provides a potential mechanism for the Great Jurassic East Asian Aridification Event, a major climate shift between 165 and 155 Ma during which Asiana's climate changed from wet and seasonal to dry, desert conditions¹⁴⁷. This was previously attributed to a rapid true polar wander event of ~20° latitude shift to south and north within ~10 Ma¹⁴⁷. Although a southward shift of 5-10° is present in our paleolatitude path for Asiana (Fig. 2C), the current temporal resolution of paleomagnetic data does not allow resolving such short-duration shifts⁹⁹, and the data and statistics that underlie this rapid latitudinal shift¹⁴⁸ are debated¹⁴⁹. Indeed, the shrinking ocean, and the closing of the Helmand-Lut gateway would have significantly reduced moisture availability along the westerly pathways, which is expected to be an important factor at these latitudes as illustrated by Cenozoic examples¹⁵⁰. Finally, the final closure of the Mongol-Okhotsk Waser ocean by the early Cretaceous enhanced land-sea latitudinal contrasts, which could have provided the condition for the onset of strong monsoons along the East and southern Asian

630 shores¹⁵¹.

631

632 4. Asiana's graveyard and East Asian geodynamics

633 The assembly of Asiana and its subsequent approach to Eurussia must also have influenced
634 East Asian mantle composition and structure. Vast amounts of oceanic lithosphere
635 subducted at multiple subduction zones, many of which were simultaneously active in the
636 Triassic. This complexity may be comparable to SE Asia and the Philippines region in the
637 Cenozoic^{97,152,153}, though Asiana assembly occurred over a much larger area that spans
638 modern east and southeast Asia. The mantle below this region still contains a memory of
639 Asiana's assembly and collision with Eurasia, known in seismic tomographic literature as the
640 'slab graveyard' that is a large high p-wave seismic velocity region overlying the core-mantle
641 boundary below Asia^{154,155} (Fig. 5).

642 To illustrate this, we placed our paleomagnetic-informed paleogeographic
643 reconstruction in a mantle reference frame adjusted to globally align tomographic anomalies
644 of subducted slabs with paleo-subduction zones in reconstructions¹⁵⁶. This reference frame
645 uses independently established kinematic correlations of subducted slabs to orogenic and
646 arc records, which revealed that lower mantle slabs sink at rates of $\sim 1\text{-}1.5\text{ cm/yr}$ ^{156,157}. Plate
647 reconstruction—slab correlation suggests that sinking occurs nearly vertically after slabs
648 break off¹⁵⁸. These correlations have shown that slabs sink to the core-mantle boundary in
649 $\sim 200\text{-}250$ million years, predicting that the remains of the Paleotethyan and Solonker oceans
650 that subducted in Permo-Triassic time currently lie on the core-mantle boundary. The
651 younger slab remains of the Mesotethys and Mongol-Okhotsk-Waser oceans are located at
652 mid-mantle depths.

653 The reconstructed position of Asiana in Triassic time covers much of the Asian slab
654 graveyard but also underlies part of the Tethyan and Mongol-Okhotsk realms (Fig. 5). This is
655 consistent with the reconstruction that the Paleotethys ocean subducted southward below
656 Qiangtang⁶¹ and northwestward below Amuria³⁷ during the assembly of Asiana, both
657 undergoing roll-back. During roll-back, slabs drape at the 660 km discontinuity, become flat-
658 lying^{159,160}, and then sink through the lower mantle as flat-lying anomalies through the lower

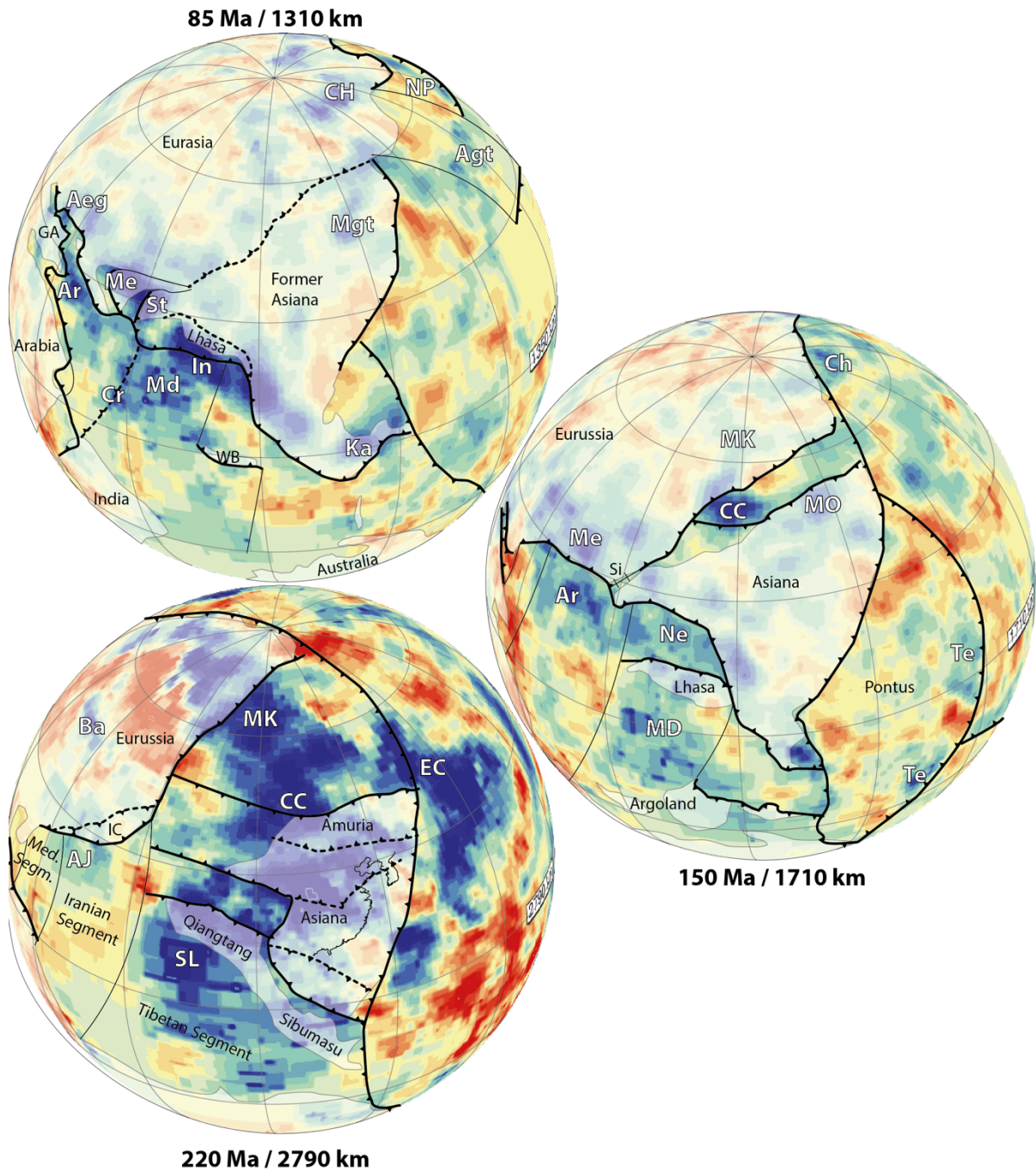
mantle^{131,161-164}. The Asian slab graveyard includes the Sri Lanka slab linked to the Paleotethys subducted below northern Qiangtang¹⁶⁴ and unnamed slabs to the northwest of the base of the Mongol-Kazakh slab that we link to Solonker subduction (Fig. 5).

Mongol-Okhotsk ocean remains have long been interpreted to correlate to an anomaly that is imaged from ~1700 km depth down to the graveyard^{6,154,156,157,165-167}. In the mid-mantle, the Mongol-Okhotsk anomaly links with another band of anomalies previously interpreted to represent remains of northwest and south-dipping Mesozoic subduction zones along the Mongol-Okhotsk ocean's margins⁶ (Fig. 5). Those interpretations followed the concept of the Mesozoic oroclinal closure of the Mongol-Okhotsk ocean—a scenario that we find no longer feasible as explained above. Instead, the southern part of the anomalies, including the lower to mid-mantle Central China anomaly^{156,157} may represent lithosphere of the southwestern part of the Waser and Mongol-Okhotsk ocean. It is located to the north of slabs linked to the Mesotethys: these include the Nepal slab that subducted northward below south Qiangtang, and the Maldives slab that is flat-lying in the mid-mantle below the Indian ocean and is linked to southward subduction below Lhasa^{161,164} (Fig. 5). To the east of the Asiana-related graveyard are slabs linked to Paleo-Pacific subduction: the East China and Chukchi slabs^{157,168,169}.

The slab graveyard that formed during Asiana assembly and its further Mesozoic evolution reveal that most of the mantle below modern East Asia, SE Asia, India, and the western Pacific has been affected by Mesozoic subduction. This covers an area far greater than elsewhere in the world, where subduction tends to have been accommodated in narrower belts for hundreds of millions of years^{157,162}. Interestingly, during and after the Triassic, the region around East Asia has seen anomalously high subduction and roll-back rates, far greater than elsewhere on Earth. The northward motion of Qiangtang occurred at ~20 cm/yr during the Middle Permian-Middle Triassic (Fig. 2D). India's northward motion between 65 and 50 Ma was up to 18 cm/yr¹⁷⁰ and the Tibetan Himalaya traveled even faster in the Late Cretaceous to Paleocene¹¹⁷. In the northwest Pacific, late Cretaceous Izanagi subduction rates reached 25 cm/yr¹⁶⁸, and similar rates were reached by convergence between the Olyutorsky arc and Kamchatka^{171,172}. These are the highest rates reconstructed for the Phanerozoic¹⁷³. Geochemical and zircon xenocryst data from mid-oceanic ridges have

689 revealed that the effects of subduction on upper mantle composition, in terms of water and
 690 sediment content, and its weakening effects on the mantle¹⁷¹, may linger for 150 million
 691 years or more¹⁷⁴⁻¹⁷⁷. It may thus be possible that the subduction history associated with
 692 Asiana preconditioned east Asia for the anomalously high plate motions, and associated
 693 geodynamic activity, since Mesozoic time.

694



695 **220 Ma / 2790 km**

696 Fig. 5. Asiana's paleogeography placed in a slab-fitted mantle reference frame¹⁵⁶, and placed

697 over horizontal slices through the UUP07 seismic tomographic model^{178,179}, with previously

identified anomalies interpreted as subducted slabs^{157,164}. Aeg = Aegean anomaly; Agt = Agattu anomaly; Ar = Arabia anomaly; Ba = Balkan anomaly; Cr = Carlsberg anomaly; CC = Central China anomaly; Ch = Chukchi anomaly; EC = East China anomaly; GA = Greater Adria; IC = Iranian Cimmerides; Ka = Kalimantan anomaly; In = India anomaly; Med. Segm. = Mediterranean Segments¹³¹; Md = Maldives anomaly; Me = Mesopotamia anomaly; MK = Mongol-Kazakh anomaly; Mg = Mongolia anomaly; Ne = Nepal anomaly; NP = North Pacific anomaly; Si = Sistan ocean; St = Sistan anomaly; SL = Sri Lanka anomaly; Te = Telkhinia anomalies; WB = West Burma block

5. Summary and Future Perspectives

In this paper, we provide apparent paleolatitudine paths for the continental fragments of East and SE Asia in the time of Pangea, from the late Paleozoic to Mesozoic, using state-of-the-art site-level based statistical analysis. These paths, combined with documented orogenic records of continental collisions, show how multiple small fragments assembled into the continent Asiana. Asiana was the largest continent, similar in size to South America, that was never part of Pangea. Instead, it moved from its assembly in the Triassic at the Northern Hemisphere (sub-)tropics over 20-30° in latitude northwards relative to Eurussia, until early Cretaceous collision and the formation of the Eurasian continent. These paleomagnetic data present the Asiana Conundrum: The conspicuous absence of a record of large-scale intra-continental shortening or an accretionary record of continental subduction suggests that convergence was accommodated by subduction of a hypothetical Mongol-Okhotsk-Waser ocean that connected the Panthalassa and Tethyan oceans. However, the intermittent arrival of large land animals such as dinosaurs to Asiana suggests that transient land bridges existed, but exactly how remains geologically unconstrained. The subducted remains of oceans that closed during Asiana assembly and its convergence with Eurasia are recognized in the mantle below Asia and the Indian ocean as the “slab graveyard” imaged by seismic tomography. The Asiana hypothesis opens the research challenges and opportunities described below.

The quantitative source of information that underpins the Asiana hypothesis and polar wander is paleomagnetism, while several first-order problems remain. The journey of Asiana to Eurussia from the middle Triassic to late Jurassic, between ~240 and 160 Ma, remains unconstrained by high-quality paleomagnetic data. This is mainly because legacy data that cover this interval cannot be corrected for well-known paleomagnetic artifacts such as inclination shallowing correction, because the original individual paleomagnetic directions or raw data were not provided. Recovery of legacy (and recent) data in FAIR databases, or resampling of sections with known age and paleomagnetic signal is critical, but also straightforward, for constraining this interval. This includes the a southward cusp of ~5° in the Asiana paleolatitude path between ~160 and 145 Ma that was interpreted as the result of fast true polar wander^{147,180,181}, correlated to similar interpretations elsewhere¹⁴⁸. However, this rapid true polar wander is debated¹⁴⁹ and the current global APWP, which has few data from this period, cannot resolve the debate⁹⁹. The data from Asiana in this interval are scattered, perhaps from the frequently reversing field in the late Jurassic, but Asiana has long records of continental sedimentary rocks that are among the most suitable on the planet to resolve this debate, and site-level statistical analysis provides the pathway to resolve such possible paleolatitudinal swings^{16,86,87}. Additionally, the Lhasa block of south Tibet provides identical ~15°S paleolatitudes from the Early Permian to the Late Triassic-Early Jurassic. This may suggest widespread remagnetization, even though most of these data pass standard paleomagnetic reliability criteria, such as fold and reversal tests. This calls for detailed study of remagnetization signals and mechanisms. Otherwise, far more complex plate tectonic scenarios of the north Gondwana margin in Permo-Triassic times than typically assumed would be required⁸⁰, and the Permian glaciations recorded in the Lhasa block would have reached tropical latitudes.

The Asiana Conundrum of a missing record of subduction despite unequivocal evidence for convergence has major implications for reconstructing paleogeography. Paleomagnetic analysis of Permian-Jurassic rocks may provide reconnaissance data to approximate where convergence was accommodated, such as between the Qaidam and Tarim blocks¹³, but detailed fieldwork and geological and geophysical mapping is also required to identify where and how convergence was accommodated and why an accretionary or arc record remain

challenging to identify. The impact is not just regional: if subduction systems – oceanic or even continental—can go unrecognized for relatively recent times of Asiana, then more subtle signatures are needed than the oceanic accretionary records typically used to identify suture zones, are needed, especially in deeper geological time. Moreover, resolving the location and nature of transient or permanent land bridges – such as intra-oceanic arcs or rotating continental arms – provide key information for paleoceanography and -climate, and biogeography.

Finally, the reconstruction of Asiana’s assembly and the resulting mantle structure leads to new opportunities to study geodynamics and deep-time climate evolution. A revision of paleogeographic boundary conditions in climate models may broaden the pallet interpret the causes of global climatic and biological events during the Late Paleozoic and Mesozoic, such as the Late Paleozoic ice age, the late Jurassic Asian aridification, and the end-Permian mass extinction. Additionally, the recent recognition that subduction-influenced mantle may remain intact and in place for 150 Myr or more¹⁷⁴⁻¹⁷⁶ opens testable dynamic hypotheses that may inspire numerical modeling to evaluate why the highest subduction rates on Earth throughout the Mesozoic and Cenozoic routinely occurred around East Asia^{168,170-173}. Moreover, modeling can test whether this anomaly underpins the unusually wide distribution of intra-continental deformation in East Asia¹⁸²⁻¹⁸⁴, Mesozoic-Cenozoic craton destruction¹⁸⁵⁻¹⁸⁷, and net lithosphere rotation^{101,188}.

Acknowledgements

S.L. and B.W. acknowledge the National Natural Science Foundation of China (NSFC, 92255303 and 42488201). Z.L. and L.D. acknowledge funding by the Key Research & Development Program from the Department of Science & Technology of Tibet (XZ202502ZY0029) and by the Excellent Research Group Program for Tibetan Plateau Earth System of the National Natural Science Foundation of China (NSFC, 42588201 to L.D.). D.J.J.v.H. was funded by Chinese Academy of Sciences President’s International Fellowship Initiative. (Grant No. 2024PG0006). P.C.L and G-R.D. acknowledge support

785 from NSF EAR Tectonics Award 1917645. We thank Erin Scott for editorial handling and
786 guidance. We thank Justin Tully for discussions about Mongolian geology.

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Supplementary Methods

We computed paleolatitude curves for continental fragments that moved on plates to the east of Pangea using the selection of reliable paleomagnetic data provided in the Supplementary Data (see Box 1 for criteria). To avoid biased estimates of paleolatitude caused by vertical-axis rotations, we compute paleolatitude-only curves by adapting the site-based approach recently developed for APWP construction^{16,22}. This approach enables incorporating temporal and spatial uncertainties and weights each dataset by the number of independent readings of the past magnetic field. We compute a paleolatitude path for each continental block with sufficient data (see Fig. 2). When two or more fragments collided to form a larger continent, we combined data from these different blocks to develop a reference curve for the combined block, a common procedure that is also widely applied to pre-Pangean continents¹². First, we re-sampled site-level data from the compiled paleopoles using their statistical descriptions¹⁶. The populations of re-sampled VGPs reflect the original site dispersion and age uncertainty behind each re-sampled pole. For a chosen reference location, we computed the paleolatitudes for each re-sampled VGP using its co-latitude, calculated as the angular distance between the VGP position and the reference location. A sliding time window with fixed length and time step was then applied to compute running mean paleolatitude estimates. Depending on the data density of the tectonic block, we used a 20 Myr (North China-Qaidam, Qiangtang, and Asiana) or 30 Myr (Lhasa) time window. We note that we removed under-determined paleolatitude estimates, i.e., computed from time windows containing only a single dataset, or when successive time windows included the exact same datasets. This procedure was repeated through 2000 bootstrap iterations, thereby propagating the uncertainties in age, where relevant in inclination shallowing correction^{22,189}, and the dispersion and size of each dataset that underpinned each paleopole into the final paleolatitude estimates. For each time step, the distribution of 2000 paleolatitude estimates yields a mean value and 95% confidence envelope defined by the 2.5 and 97.5 percentiles, following site-level paleomagnetic statistical procedures^{16,22}.

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