Impact of Tibetan Plateau Uplift and Neo-Tethys Sea Retreat on Stepwise Climate Aridification in Asian Mid-latitudes Postprint

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Abstract

The Asian interior represents the largest and most extensive mid-latitude arid region in the Northern Hemisphere, differing from arid regions elsewhere in the world that are distributed under subtropical high-pressure control. The contemporary mid-latitude arid region of Asia is located deep within the continental interior, far from moisture sources of the major oceans. How exactly did the mid-latitude arid region of Asia form? What aridification processes has it experienced? What are the dynamic mechanisms underlying its formation and evolution? These have long been unresolved questions. In fact, the development of the mid-latitude arid region of Asia into the arid desert observed today was not achieved within a short period, but rather underwent a prolonged, staged evolutionary process. Under the combined influence of regional and global factors since the Cenozoic—including the collision of the Indian, Arabian, and African plates with the Eurasian continent, the uplift of the Tibetan Plateau, the retreat of the Neo-Tethys Sea, and Cenozoic global climate cooling and sea-level decline—it progressively evolved from semi-humid through semi-arid to arid and ultimately hyper-arid conditions. This evolution encompassed a semi-humid climate during the Eocene, a semi-humid to semi-arid climate during the Oligocene, and an arid to hyper-arid climate since the late Miocene.

Full Text

Effects of Tibetan Plateau Uplift and Neotethys Ocean Retreat on the Stepwise Aridification of Mid-latitude Asia

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Abstract

The Asian interior represents the largest and most extensive mid-latitude arid zone in the Northern Hemisphere, fundamentally distinct from arid regions controlled by subtropical high-pressure systems. Situated deep within the Eurasian continent, modern mid-latitude Asia remains far removed from oceanic moisture sources. How did this vast arid region form? What aridification processes has it undergone? What mechanisms drove its formation and evolution? These questions have long remained unresolved. In reality, the development of today’ s desert environment in mid-latitude Asia was not a rapid event but rather a prolonged, stepwise evolutionary process spanning millions of years. Through the Cenozoic, the region progressively transformed from semi-humid to semi-arid, then to arid, and finally to hyper-arid conditions, driven by the combined effects of the collision between Indian, Arabian, and African plates with Eurasia, uplift of the Tibetan Plateau, retreat of the Neotethys Ocean, and global climate cooling with associated sea-level decline. This evolution encompassed a semi-humid climate during the Eocene, a semi-humid to semi-arid climate in the Oligocene, and an arid to hyper-arid climate since the late Miocene.

Keywords: mid-latitude arid zone, Cenozoic long-term evolution, aridification, forcing mechanism

The Asian interior constitutes the largest mid-latitude arid zone in the Northern Hemisphere [Figure 1: see original paper], spanning southern Mongolia, the region north of China’s Loess Plateau, three major inland basins in northwestern China, and arid areas of Central Asia—an important region traversed by the overland Silk Road. Unlike arid zones controlled by subtropical high-pressure systems elsewhere in the world (such as the Sahara Desert and Middle Eastern deserts), this arid region is situated in mid-latitudes. Conversely, the middle and lower Yangtze River region, which should be under subtropical high control, has become a “land of fish and rice” with abundant precipitation due to the influence of the Asian monsoon.

Modern mid-latitude Asia lies deep in the continental interior, far from oceanic moisture sources [Figure 1: see original paper]. Moisture from the Indian Ocean is blocked by the Himalayas; Pacific moisture is largely depleted before reaching Central Asia after its long journey; and westerly moisture from the Atlantic and

Mediterranean is mostly exhausted over the European continent, with limited residual moisture further obstructed by the Pamir, Hindu Kush, Tian Shan, and Altai mountains. Consequently, mid-latitude Asia has become the most extensive arid region in the Northern Hemisphere.

How did this mid-latitude Asian arid zone gradually develop into its current desert landscape? What aridification processes did it experience? What dynamic mechanisms governed its formation and evolution? What roles did regional and global factors—including Cenozoic collisions of the Indian, Arabian, and African plates with Eurasia, Tibetan Plateau uplift, Neotethys retreat, and global climate cooling with sea-level decline—play in this process? These remain outstanding questions. The development of today' s desert environment in mid-latitude Asia was not a short-term phenomenon but a prolonged geological process involving stepwise evolution from semi-humid through semi-arid to arid and finally hyper-arid conditions. This paper attempts to explore the stepwise aridification of mid-latitude Asia based on previous research and recent findings.

Eocene Semi-humid Paleoenvironment

The transformation of mid-latitude Asia into today' s extensive arid zone has profound tectonic underpinnings. The most recent supercontinent assembly occurred during the Pangaea episode ~250 million years ago, but Pangaea began rifting from ~230 million years ago. Rifting of the southern Gondwana continent intensified after the Cretaceous (94 million years ago), with African and Indian plates detaching from Antarctica and drifting northward. By ~60 million years ago, the leading edge of the Indian plate had collided with Asia' s southern margin along the middle Yarlung-Zangbo suture zone [1-3]. However, collision at the eastern and western syntaxes of the India-Asia collision zone is generally considered to have occurred later, with complete collision not achieved until ~50 million years ago [2].

Not only was the Indian plate drifting northward, but the African plate was as well. Their convergence with Eurasia accelerated the contraction of the Neotethys Ocean. During the early Eocene, 50 million years ago [Figure 2: see original paper], regional tectonic evolution had already influenced Central Asian paleoclimate. Recent studies indicate that after the Indian subcontinent rifted from Gondwana and drifted across the equator into the Intertropical Convergence Zone (ITCZ), the South Asian monsoon had already formed, as confirmed by early Eocene numerical simulations [4]. Shukla and Mehrotra [5] discovered early Eocene (55–52 million years ago) coal-bearing strata in Rajasthan, northwestern India, indicating a humid climate. Analysis of abundant broadleaf plant fossils suggests precipitation reached 1,800 mm/year with distinct wet and dry seasons, demonstrating that the South Asian monsoon may have existed 50 million years ago.

It should be noted that India and Asia had completely collided by 50 million years ago, and mountain uplift along the collision boundary [7] would have at least partially blocked the South Asian monsoon from penetrating deep into the Asian continent. Furthermore, despite Africa-India-Eurasia collision reducing the extent of the Neotethys Ocean, vast marine areas still existed in what is now Central Asia and regions to the west, allowing westerly circulation to transport substantial moisture into Central Asia.

Even by the late Eocene (~40 million years ago), seawater had only just retreated from the Tarim Basin [8,9], consistent with Carrapa’ s [10] conclusion that marine regression at the westernmost Alai Strait connecting the Tarim and Tajik basins (easternmost Tajik Basin) occurred 39 million years ago—the Tarim Basin east of the Alai Strait could not have been later. However, the late Eocene seawater retreat from the Tarim Basin was primarily related to northward protrusion of the Pamir Plateau. At this time, most of the Tajik Basin west of the Pamir and regions further west remained covered by extensive seas. Moreover, the Pamir Plateau had not yet collided with the southern Tian Shan, leaving at least a 300-kilometer moisture pathway between them [11]. The Tian Shan mountains had not yet undergone tectonic reactivation and remained low-elevation features after prolonged Mesozoic erosion [12]. Moisture could still be transported to Central Asia by prevailing westerlies. Both the Suweiyi Formation in the Tarim Basin [13] and the Ziniquanzi Formation in the Junggar Basin [14] consist primarily of lacustrine strata, while southern Mongolia in the late Eocene also featured lacustrine-fluvial depositional environments [15]. This indicates that Central Asia was at least semi-humid during this period.

Oligocene Semi-humid to Semi-arid Paleoenvironment

By the early Oligocene, 34 million years ago, intensified convergence of African, Indian, and Eurasian plates directly caused further Tibetan Plateau uplift and Neotethys contraction [Figure 3: see original paper]. Additionally, the early Oligocene witnessed the most important climatic event in Cenozoic cooling—the formation of the Antarctic ice sheet, marking the transition from “greenhouse” to “icehouse” conditions with associated global sea-level decline.

Under combined effects of continental convergence and sea-level fall, the previously unified Neotethys Ocean was split into southern and northern branches, with the northern branch called the Paratethys Sea [Figure 3: see original paper]. By the early Oligocene, the central Tibetan Plateau had risen to near 3,000 meters elevation [16-18]. Although some foreign scholars have used carbonate oxygen isotope paleoaltimetry to suggest the central plateau approached modern elevations in the Oligocene [19,20], both soil and lacustrine carbonate oxygen isotope paleoaltimeters have unavoidable issues—oxygen isotope fractionation is strongly influenced by moisture sources and carbonate diagenetic resetting, severely compromising reliability. Tibetan Plateau uplift undoubtedly more effectively blocked the South Asian monsoon from penetrating deep into Asia, with its rain shadow effect becoming pronounced. The East Asian monsoon had not yet formed in the Oligocene [4,21,22], leaving westerly moisture as the primary source for mid-latitude Asia [23].

Although the Paratethys Sea’ s extent had shrunk compared to the Eocene, the Pamir had not yet collided with the southern Tian Shan, leaving the moisture pathway from the Atlantic and Paratethys still open [24]. Moreover, the Tian Shan remained a low-elevation range that had not undergone tectonic reactivation [12], allowing westerlies to transport moisture from the Atlantic and Neotethys into Central Asia. However, reduced upwind moisture sources meant less moisture reached mid-latitude Asia, initiating semi-arid conditions in the continental interior. In southern Mongolia, the most distant from Paratethys moisture sources, eolian red clay deposition began in the early Oligocene [15].

However, Oligocene eolian red clays in Mongolia contain paleosol and carbonate nodule layers, indicating at least semi-arid rather than hyper-arid conditions. Pedogenic carbonate nodule formation requires sufficient moisture for chemical leaching, so their presence precludes extreme aridity. Regional geological surveys in Mongolia have also found no ancient dune deposits; the Oligocene red clay deposits represent dust transported from piedmont alluvial fans and dry paleochannels.

Around the late Oligocene, eolian red clay deposition also began in areas west of the Liupan Mountains on the Loess Plateau and in the Junggar Basin of Xinjiang [21,25,26]. These eolian red clays similarly contain paleosols and carbonate nodules, demonstrating sufficient moisture for chemical leaching. As dust accumulations rather than sand deposits, they indicate steppe-to-dry-steppe semi-humid to semi-arid environments.

Late Miocene Aridification of Central Asia

Since the late Miocene, India-Asia collision continued while the Arabian plate collided with Asia in the late Miocene, causing uplift of the Iranian Plateau [27,28]. The African plate also continued converging with Eurasia, further driving Paratethys retreat. Additionally, since 14 million years ago, continued expansion of the East Antarctic ice sheet [29] caused persistent sea-level decline. Under combined effects of plate convergence and global cooling, the once-vast Paratethys Sea had substantially retreated by the late Miocene [Figure 4: see original paper].

More importantly, abundant geological evidence indicates that during the late Miocene (7–5 million years ago), the northern Pamir front collided with the southern Tian Shan, activating the Pamir frontal thrust [30-33] and gradually closing the moisture pathway into the Tarim Basin [Figure 5: see original paper], accelerating the onset of extreme aridity. During this period, although the Mazartag section in central Tarim and Lop Nur drill cores still show lacustrine-dominated deposition [33,34], sporadic ancient eolian sand interlayers appear in late Miocene lacustrine strata at the Mazartag section, signaling the beginning of extreme arid conditions. While the aridification history of the Tarim Basin remains debated [35-38], more evidence indicates significantly drier conditions emerged since 5 million years ago [33,34,39-41]. Lacustrine strata disappeared, replaced by fluvial and eolian sand deposits, as the Tarim Basin transitioned toward hyper-arid conditions.

This aligns with geological records of intensified aridification in the Qaidam Basin since the Pliocene, indicated by extraordinarily robust bones of the fish *Hsianwenia* [42], and with evidence of late Miocene aridification from other Central Asian regions [43].

Although the formation timing of other Chinese deserts (Badain Jaran, Tengger, Ulan Buh, Kubuqi, Mu Us) remains unclear, the widespread distribution of late Miocene (8-7 million years ago) Tertiary eolian red clay east of the Liupan Mountains on the Chinese Loess Plateau [44-48] indicates that the Central Asian arid-to-semi-arid source area had already taken shape during this period.

References

1. DeCelles P, Kapp P, Gehrels G, et al. Paleocene-Eocene foreland basin evolution in the Himalaya of southern Tibet and Nepal: implications for the age of initial India-Asia collision. *Tectonics*, 2014, 33(5): 824-849.
2. Wu F Y, Ji W Q, Wang J G, et al. Zircon U-Pb and Hf isotopic constraints on the onset time of India-Asia collision. *American Journal of Science*, 2014, 314: 548-579.
3. Hu X M, Garzanti E, Wang J G, et al. The timing of India-Asia collision onset at the Selandian (middle Paleocene, 59±1 Ma). *Geology*, 2015, 43: 859-862.
4. Liu X D, Dong B W, Yin Z Y, et al. Continental drift and plateau uplift control origination and evolution of Asian and Australian monsoons. *Scientific Reports*, 2017, 7: 40344.
5. Shukla A, Mehrotra A C. Early Eocene (~50 Myr) legume fruits from Rajasthan. *Current Science*, 2016, 111: 465-467.
6. Blakey R. Global paleogeography. [2017-09-13]. http://jan.ucc.nau.edu/rcb7/.
7. Ding L, Xu Q, Yue Y H, et al. The Andean-type Gangdese Mountains: Paleoelevation record from the Paleocene-Eocene Linzhou Basin. *Earth and Planetary Science Letters*, 2014, 392: 250-264.
8. Bosboom R E, Dupont-Nivet G, Grothe A, et al. Linking Tarim Basin sea retreat (West China) and Asian aridification in the late Eocene. *Basin Research*, 2014, 26: 621-640.
9. Zheng H B, Wei X C, Tada R, et al. Late Oligocene-early Miocene birth of the Taklimakan Desert. *PNAS*, 2015, 112: 7662-7667.

10. Carrapa B. Eocene Paratethys regression in the Tajik basin of central Asia: implications for the age of the Tarim Basin sea retreat. *Earth and Planetary Science Letters*, 2015, 424: 168-178.
11. Burtman V S, Molnar P. Geological and geophysical evidence for deep subduction of continental crust beneath the Pamir. *Geological Society of America Special Paper*, 1993, 281: 1-76.
12. Tapponnier P, Molnar P. Active faulting and Cenozoic tectonics of the Tien Shan, Mongolia and Baykal regions. *Journal of Geophysical Research*, 1979, 84 (B7): 3425-3459.
13. 新疆维吾尔自治区地质矿产局. 新疆维吾尔自治区区域地质志. 北京: 地质出版社, 1993.
14. Charreau J, Blard P H, Puchol N, et al. An early Pleistocene and modern denudation rate for the Chinese Tian Shan from cosmogenic nuclides. *Earth and Planetary Science Letters*, 2011, 304: 85-92.
15. Meng Q Q, Wu X H, Cao K, et al. Late Eocene onset of Tarim Basin desertification. *Geology*, 2015, 43: 515-518.
16. Rowley D B, Currie B S. Palaeo-altimetry of the late Eocene to Miocene Lunpola basin, central Tibet. *Nature*, 2006, 439: 677-681.
17. Polissar P J, Freeman K H, Rowley D B, et al. Paleoaltimetry of the Tibetan Plateau from D/H ratios of lipid biomarkers. *Earth and Planetary Science Letters*, 2009, 287: 64-76.
18. Linnemann U, Su L, Hofmann M, et al. New U-Pb dates from the Kelasu section in the Baicheng depression, Southern Tian Shan, northwestern China. *Journal of Asian Earth Sciences*, 2015, 111: 17-37.
19. Rowley D B, Currie B S. Palaeo-altimetry of the late Eocene to Miocene Lunpola basin, central Tibet. *Nature*, 2006, 439: 677-681.
20. Polissar P J, Freeman K H, Rowley D B, et al. Paleoaltimetry of the Tibetan Plateau from D/H ratios of lipid biomarkers. *Earth and Planetary Science Letters*, 2009, 287: 64-76.
21. Sun J M, Zhang L Y, Deng C L, et al. Evidence for desertification by 22 Myr ago inferred from loess deposits in China. *Nature*, 2002, 416: 159-163.
22. Sun X J, Wang P X. How old is the Asian monsoon system? Palaeobotanical records from China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 2005, 222: 181-222.
23. Caves J K, Winnick M J, Graham S A, et al. Role of the westerlies in Central Asia climate over the Cenozoic. *Earth and Planetary Science Letters*, 2015, 428: 33-43.
24. Cowgill E, Yin A, Harrison T M, et al. Reconstruction of the Altyn Tagh Fault based on U-Pb geochronology: Role of back thrusts, mantle sutures,

and heterogeneous crustal strength in forming the Tibetan Plateau. *Journal of Geophysical Research*, 2003, 108: 2346.

25. Fang X M, Lü L Q, Yang S L, et al. Loess in Kunlun Mountains and its implications on desert development and Tibetan Plateau uplift in west China. *Science China (Series D)*, 2002, 45: 289-299.
26. Sun D H, Bloemendal J, Yi Z Y, et al. Palaeomagnetic and palaeoenvironmental study of two parallel sections of late Cenozoic strata in the central Taklimakan Desert: implications for the desertification of the Tarim Basin. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 2011, 300: 1-10.
27. Mouthereau F, Lacombe O, Vergés J. Building the Zagros collisional orogen: Timing, strain distribution and the dynamics of Arabia/Eurasia plate convergence. *Tectonophysics*, 2012, 532-535: 27-60.
28. Khadivi S, Mouthereau F, Lacombe O, et al. Exhumation history of the High Zagros fold-thrust belt, Iran, from (U-Th)/He thermochronometry. *Tectonics*, 2010, 29(4): TC4025.
29. Zachos J, Pagani M, Sloan L, et al. Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science*, 2001, 292: 686-693.
30. Fu B H, Ninomiya Y, Guo J M. Slip partitioning in the northeast Pamir-Tian Shan convergence zone. *Tectonophysics*, 2010, 483: 344-364.
31. Cao K, Wang G, van der Beek P, et al. Cenozoic thermo-tectonic evolution of the northeastern Pamir revealed by zircon and apatite fission-track thermochronology. *Tectonophysics*, 2013, 589: 17-32.
32. Thompson J A, Burbank D W, Tao L, et al. Late Miocene northward propagation of the northeast Pamir thrust system, northwest China. *Tectonics*, 2015, 34: 510-534.
33. Sun J M, Liu W G, Liu Z H, et al. Extreme aridification since the beginning of the Pliocene in the Tarim Basin, western China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 2017 (in press).
34. Liu W G, Liu Z H, An Z S, et al. Late Miocene episodic lakes in the arid Tarim Basin, western China. *PNAS*, 2014, 111: 16292-16296.
35. Fang X M, Lü L Q, Yang S L, et al. Loess in Kunlun Mountains and its implications on desert development and Tibetan Plateau uplift in west China. *Science China (Series D)*, 2002, 45: 289-299.
36. Sun J M, Alloway B, Fang X, et al. Refuting the evidence for an earlier birth of the Taklimakan Desert. *PNAS*, 2015, 112: 5556-5557.
37. Zheng H B, Wei X C, Tada R, et al. Late Oligocene–early Miocene birth of the Taklimakan Desert. *PNAS*, 2015, 112: 7662-7667.
38. Chang H, An Z S, Liu W G, et al. Magnetostratigraphic and paleoenvironmental records for a late Cenozoic sedimentary sequence drilled from

Lop Nur in the eastern Tarim Basin. *Global and Planetary Change*, 2012, 80-81: 113-122.

39. Sun D H, An Z S. Late Pliocene-Pleistocene changes in mass accumulation rates of eolian deposits on the central Chinese Loess Plateau. *Journal of Geophysical Research*, 2005, 110: D23101.
40. Liu X D, Dong B W, Yin Z Y, et al. Continental drift and plateau uplift control origination and evolution of Asian and Australian monsoons. *Scientific Reports*, 2017, 7: 40344.
41. Caves J K, Bayshashov B U, Zhamangara A, et al. Late Miocene Uplift of the Tian Shan and Altai and Reorganization of Central Asia Climate. *GSA Today*, 2016, 27(2): doi: 10.1130/GSATG305A.1.
42. Wang X, Wang Y, Zhang C, et al. A boned fish linked to the aridification of the Qaidam Basin (northern Tibetan Plateau). *PNAS*, 2008, 105: 13246-13251.
43. Caves J K, Bayshashov B U, Zhamangara A, et al. Late Miocene Uplift of the Tian Shan and Altai and Reorganization of Central Asia Climate. *GSA Today*, 2016, 27(2): doi: 10.1130/GSATG305A.1.
44. An Z S, Kutzbach J E, Prell W L, et al. Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan plateau since Late Miocene times. *Nature*, 2001, 411: 62-66.
45. Ding Z L, Sun J M, Yang S L, et al. Preliminary magnetostratigraphy of a thick eolian red clay-Loess sequence at Lingtai, the Chinese Loess Plateau. *Geophysical Research Letters*, 1998, 25: 1225-1228.
46. Sun D H, Shaw J, An Z S, et al. Magnetostratigraphy and paleoclimatic interpretation of a continuous 7.2 Ma Late Cenozoic eolian sediments from the Chinese Loess Plateau. *Geophysical Research Letters*, 1998, 25: 85-88.
47. Guo Z T, Peng S Z, Hao Q Z, et al. Late Miocene-Pliocene development of Asian aridification as recorded in an eolian sequence in northern China. *Global and Planetary Change*, 2004, 41(3-4): 135-145.
48. Sun D H, An Z S, Tada R, et al. Pliocene red clay formation in central Loess Plateau, China. *Earth and Planetary Science Letters*, 1998, 161: 135-143.

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Note: Figure translations are in progress. See original paper for figures.