

Constraints on the early uplift history of the Tibetan Plateau

Chengshan Wang^{*†}, Xixi Zhao^{*†}, Zhifei Liu[§], Peter C. Lippert[‡], Stephan A. Graham[¶], Robert S. Coe[‡], Haisheng Yi^{||}, Lidong Zhu^{||}, Shun Liu^{||}, and Yalin Li^{*}

^{*}State Key Laboratory of Geological Processes and Mineral Resources, Research Center for Tibetan Plateau Geology, and School of Geosciences, China University of Geosciences, Beijing 100083, People's Republic of China; [‡]Department of Earth and Planetary Sciences and Institute of Geophysics and Planetary Physics, University of California, Santa Cruz, CA 95064; [§]Laboratory of Marine Geology, Tongji University, Shanghai 200092, People's Republic of China; [¶]Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305; and ^{||}School of Geosciences, Chengdu University of Technology, Chengdu 610059, People's Republic of China

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The surface uplift history of the Tibetan Plateau and Himalaya is among the most interesting topics in geosciences because of its effect on regional and global climate during Cenozoic time, its influence on monsoon intensity, and its reflection of the dynamics of continental plateaus. Models of plateau growth vary in time, from pre-India-Asia collision (e.g., ≈ 100 Ma ago) to gradual uplift after the India-Asia collision (e.g., ≈ 55 Ma ago) and to more recent abrupt uplift (< 7 Ma ago), and vary in space, from northward stepwise growth of topography to simultaneous surface uplift across the plateau. Here, we improve that understanding by presenting geologic and geophysical data from north-central Tibet, including magnetostratigraphy, sedimentology, paleocurrent measurements, and $^{40}\text{Ar}/^{39}\text{Ar}$ and fission-track studies, to show that the central plateau was elevated by 40 Ma ago. Regions south and north of the central plateau gained elevation significantly later. During Eocene time, the northern boundary of the proto-plateau was in the region of the Tanggula Shan. Elevation gain started in pre-Eocene time in the Lhasa and Qiangtang terranes and expanded throughout the Neogene toward its present southern and northern margins in the Himalaya and Qilian Shan.

climate | tectonics | magnetostratigraphy | Hoh Xil Basin | Cenozoic

The Tibetan Plateau is the most extensive region of elevated topography in the world (Fig. 1). How such high topography, which should have an effect on climate, monsoon intensity, and ocean chemistry (1–5), has developed through geologic time remains disputed. Various lines of investigation, including evidence from the initiation of rift basins (6), potassium-rich (K-rich) volcanism (7), tectonogeomorphic studies of fluvial systems and drainage basins (8), thermochronologic studies (9), upper-crustal deformation histories (10, 11), stratigraphic and magnetostratigraphic studies of sediment accumulation rates (12), paleobotany (13), and oxygen isotope-based paleoaltimetry (14–22), have suggested different uplift histories. Authors of recent geologic studies (11) have proposed that significant crustal thickening (and by inference, surface uplift) in the Qiangtang terrane occurred in the Early Cretaceous [≈ 145 mega-annum (Ma) age], followed by major crustal thickening within the Lhasa terrane between ≈ 100 and 50 Ma ago. This hypothesis remains disputed (23). Other models of plateau growth range from Oligocene (e.g., ≈ 30 Ma ago) gradual surface uplift (7) to more recent (< 7 Ma ago) and abrupt surface uplift (24), with oblique stepwise growth of elevation northward and eastward after the India-Eurasia collision (7, 20, 25, 26). With few exceptions (e.g., see refs. 11 and 27), most of these models focus on data from the Himalaya and southern Tibet and remain relatively unconstrained by geologic data from the interior of the Tibetan Plateau.

The Hoh Xil Basin (HXB) of the north-central Tibetan Plateau (Figs. 1 and 2) is the most widespread exposure of Paleogene sediments on the high plateau and contains $> 5,000$ m of Cenozoic nonmarine strata (28). Although the HXB (5,000-m average elevation) is a part of the high plateau today, it once was a basin

bounding the northern boundary of the Paleogene proto-Tibetan Plateau. The HXB, characterized by low-gradient fluvial and lacustrine facies, may be an analogue of the Qaidam or Tarim basin systems on the northern margins of the modern high plateau, which are a variety of foreland basins termed “collisional successor basins” by Graham *et al.* (29). Here, we argue that the HXB is a foreland basin system that developed in concert with the rise and erosion of adjacent high mountain belts. Specifically, our work supports the idea that HXB evolution was coeval with the surface uplift of the Qiangtang terrane to the south and that high elevation characterized the central Tibetan Plateau by Eocene time.

Sedimentology and Magnetostratigraphy of the HXB

HXB sediments are exposed most extensively in the Fenghuo Shan (“shan” means “mountain” in Chinese) region and can be divided into three lithostratigraphic units. The basal Fenghuoshan Group (FG) consists of cobble-pebble conglomerate, red sandstone, and bioclastic limestone of fluvial, fan-delta, and lacustrine origin. The overlying Yaxicuo Group (YG) is distinguished by sandstone, mudstone, marl, and gypsum deposited in fluvial and playa environments. A pronounced angular unconformity separates the YG from the overlying Wudaoliang Group (WG), which consists of lacustrine marl and minor amounts of black oil shale. The FG and YG together are $> 5,000$ m thick and deformed by overturned folds and numerous south-directed thrusts, whereas the 100- to 200-m-thick WG is only gently tilted.

Nearly 300 paleocurrent measurements indicate that the paleoflow direction recorded in the FG is dominantly northward (Fig. 2), consistent with provenance studies and proximal-to-distal facies distributions that show that detritus in the HXB was derived from the Qiangtang terrane to the south (30) and controlled by the Tanggula thrust system [for data, see supporting information (SI) Figs. 7 and 8 in *SI Appendix*]. Paleocurrent indicators in the YG are also directed to the north in its lower part but are increasingly deflected eastward higher in the section, with some southerly indicators at the top of the section (Fig. 2). Thus, paleoflow indicators are mainly directed northward away from the Tanggula Shan front and eastward parallel to the front.

Chinese workers traditionally have regarded the initiation of the HXB as Cretaceous on the basis of pollen biostratigraphy

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[†]To whom correspondence may be addressed. E-mail: chshwang@cugb.edu.cn or xzhao@pmc.ucsc.edu.

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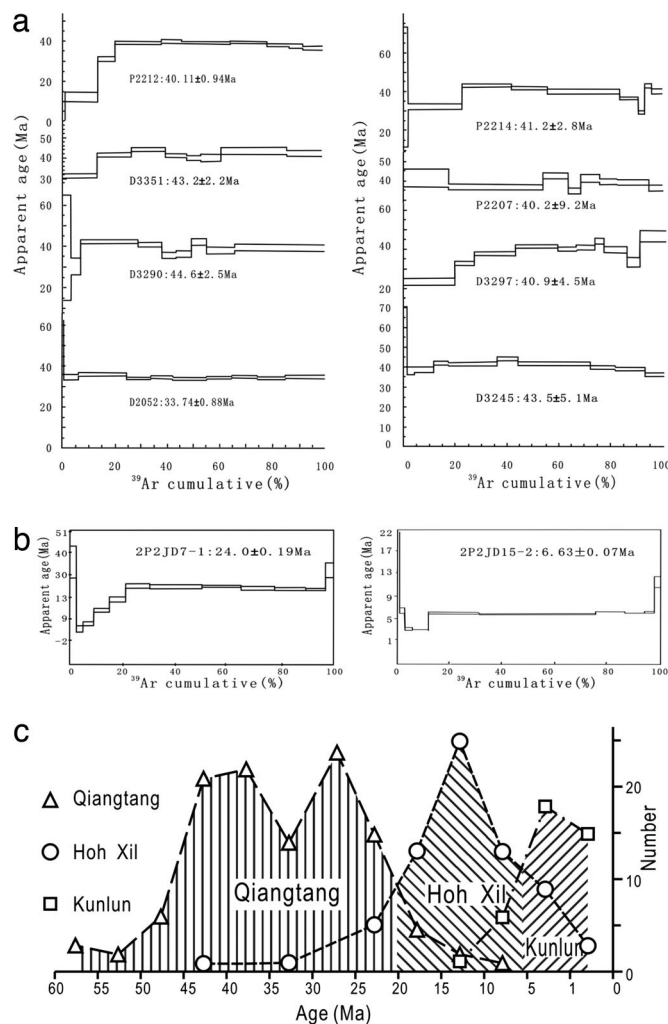


Fig. 4. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages from this study. (a) Zhuerkenwula mountains, which is the largest Cenozoic volcanic province in the northern Tibetan-Kunlun region ($\approx 2,500 \text{ km}^2$). The K-rich lavas in this province were previously considered to be $<20 \text{ Ma}$ old. (b) Plateau ages from the Hoh Xil region. (c) Distributions of radiometric dates of K-rich lavas from the Qiangtang, Hoh Xil, and Kunlun belts (>200 dates collected, mainly from refs. 39 and 60).

uplift and high elevations because previously reported K-rich volcanics from western Qiangtang are $\approx 20 \text{ Ma}$ old or younger (Fig. 1) (7). Our $^{40}\text{Ar}/^{39}\text{Ar}$ geochronologic study of a recently discovered volcanic province in the Zhuerkenwula mountain area (Figs. 3 and 4a) reveals that K-rich volcanism began in western Qiangtang at least 33.7–43.5 Ma ago. Calc-alkaline volcanic rocks of Eocene-Oligocene age were also documented recently in southern Qiangtang (40). In the HXB, however, most K-rich lava units are even younger (6–24 Ma; Fig. 4 b and c) and overlie redbeds of the foreland basin. Thus, east-west diachronous uplift of the Tibetan Plateau is not supported by the ages of K-rich lavas, which actually young northward from the Qiangtang terrane to the Kunlun Shan (Fig. 4c). Whether these melts are the product of lithospheric thinning or intracontinental subduction (35, 41) remains a topic of active research.

Discussion

When did regional surface uplift commence? The transition from marine to terrestrial facies is one of the most direct lines of evidence for uplift. The youngest marine strata of the Qiangtang terrane are Lower Cretaceous, whereas those of the Lhasa terrane are Late

Cretaceous (Fig. 5). These folded deposits are unconformably overlain by Upper Cretaceous and Paleogene nonmarine deposits, as imaged by recent seismic profiling in the region (SI Fig. 11 in *SI Appendix*) and mapped in outcrop (11, 42). This structural-stratigraphic relationship indicates that crustal shortening, thickening, and surface uplift were active in both the Qiangtang and Lhasa terranes well before the Early Eocene (10). South of the Lhasa terrane, recent biostratigraphic studies in the Himalayan terrane confirm the record of Paleocene marine deposition in both the northern and southern Tethyan Himalaya (43, 44). Importantly, our work demonstrates that the marine Penqu Formation near Tingri is latest Eocene in age (Priabonian, calcareous nannofossil zone NP20), extending the age of marine incursion in the southern Tethyan Himalaya by $\approx 5 \text{ Ma}$ (44). We also have directly dated an Early Eocene (zone of *Buryella clinata*–*Thursocyrtes ampla*) radiolarian chert in Saga County in the northern Tethyan Himalaya (SI Fig. 12 in *SI Appendix*), where previous studies have only inferred a mid-Paleogene age on the basis of Paleocene biostratigraphy and stratigraphic relationships (43, 45). Thus, by using the disappearance of marine facies as a measure of early surface uplift, we conclude that the emergence of the Himalaya occurred post-Eocene at the earliest, possibly even more recently. Oxygen isotope-based paleoaltimetry studies from the Thakkhola graben and Gyirong basin suggest that the Tethyan Himalaya were at or near modern elevation by the mid-Miocene (14, 15). Collectively, these studies are consistent with the sedimentary record of Himalayan orogenesis (46) and indicate significant southward elevation gain between 40 and $\approx 12 \text{ Ma}$ ago.

When the proto-Tibetan Plateau (the Lhasa and Qiangtang terranes) reached its modern elevation remains uncertain (26), although regional paleoaltimetry studies provide some constraints. Independent paleoaltimetry estimates from the Namling-Oiyung basin in southern Tibet (13, 17) suggest that the elevation of the southern Tibetan Plateau has remained at $\approx 4.6 \text{ km}$ since 15 Ma ago. Farther north, chronologically well constrained stable-isotope studies from the Nima basin along the Bangong–Nujiang suture between the Lhasa and Qiangtang terranes suggest that this region was high and dry, similar to the modern environment, by the Early Oligocene (22). Oxygen isotope studies of Paleogene strata in the Lunpola basin, which also spans the Bangong–Nujiang suture, suggest that the region was 4.0–4.6 km high (20) by the Early Oligocene (22). Paleoaltimetry estimates from the Hoh Xil region are equivocal. Cyr *et al.* (18) used oxygen isotope values from lacustrine carbonates from the FG and modeled monsoon-dominated isotopic lapse rates to argue that the HXB was $\approx 2 \text{ km}$ high during the Late Eocene, whereas DeCelles *et al.* (22) reevaluated these data by using lower, empirically based lapse rates from central Tibet and argue that the HXB was 4.7–5.0 km high during the Late Eocene.

Our evidence from stratigraphy, geochronology of K-rich lavas, and apatite fission-track studies, as well as the paleoaltimetry studies discussed above, support the idea that the Lhasa and southern Qiangtang terranes were at or near their modern elevation since 40 Ma and formed the proto-Tibetan Plateau (Fig. 6). The northern edge of the Tanggula Shan formed the northern margin of the proto-Tibetan Plateau, whereas the Gangdese arc formed the southern boundary, consistent with the inferences of Kapp *et al.* (11, 47) and Spurlin *et al.* (34). Oligocene–Early Miocene upper-crustal shortening within the HXB would have been driven by Indo-Asian collisional stresses from the south transmitted across this high proto-Tibetan Plateau and localized along its northern boundary. Thus, we argue that the Tibetan Plateau grew southward and northward from a nucleus of high topography (Fig. 6), consistent with predictions based on simple physical considerations (48, 49). Surface uplift to 5,000 m in the HXB region was probably achieved by a combination of upper-crustal shortening (50), continental underthrusting of the Lhasa and Songpan–Ganzi terranes beneath Qiangtang (11), and mantle dynamics (36).

equations (56) that relate time, temperature, fission-track length, and fission-track density were used to extract age, track-length, and thermal history data.

Paleocurrents Direction Determination. Paleocurrent directions were measured from primary sedimentary structures, including cross stratification, pebble imbrication, and ripple crest orientation. The orientations of paleocurrent indicators were measured in the field with a Brunton compass. For planar paleocurrent indicators (cross-strata, pebble-cobble imbrication), the strike and dip of the planar feature were measured. Structural restoration of paleocurrent data were made by using a computer-based stereonet program.

Radiolarian Biostratigraphy. Ten radiolarian samples were analyzed at the Institute of Geological Sciences (Jagiellonian University, Krakow, Poland). Samples were processed following the procedures described in ref. 57. Samples were

treated with 50% hydrochloric acid for 48 h to remove calcium carbonate and organic carbon and finely sieved (61 μm) with water to remove the fine fraction. The radiolarian species present and abundances were recorded following ref. 58.

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