Pre-Miocene birth of the Yangtze River

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Abstract

The development of fluvial systems in East Asia is closely linked to the evolving topography following India-Eurasia collision. Despite this, the age of the Yangtze River system has been strongly debated, with estimates ranging from 40 to 45 Ma, to a more recent initiation around 2 Ma. Here, we present 40Ar/39Ar ages from basalts interbedded with fluvial sediments from the lower reaches of the Yangtze together with detrital zircon U–Pb ages from sand grains within these sediments. We show that a river containing sediments indistinguishable from the modern river was established before ~23 Ma. We argue that the connection through the Three Gorges must postdate 36.5 Ma because of evaporite and lacustrine sedimentation in the Jianghan Basin before that time. We propose that the present Yangtze River system formed in response to regional extension throughout eastern China, synchronous with the start of strike-slip tectonism and surface uplift in eastern Tibet and fed by strengthened rains caused by the newly intensified summer monsoon.

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Major river systems are responsible both sculpting the landscape over large areas of the continental crust, as well as controlling the development of offshore geology along continental margins. Despite this significance it is often unclear why major river systems are initially formed and what processes influence their development. The Yangtze River is one of the largest in East Asia and has been the subject of debate for more than a century (1). Despite disagreement on the timing of its establishment most geologists agree that the development of this river represents a response to the evolving topography and climate of East Asia (2).

Uplift of the Tibetan Plateau and subsidence in eastern China, following the cessation of Cretaceous arc magmatism within the Cathaysia block during the Cenozoic (3) have acted to reverse an elevation in Asia means that constraining when the modern rivers achieved their present geometry is important because of their sensitivity to the changing regional topographic gradient. A proposed Pleistocene age for the Yangtze largely hinges on evidence that the modern delta had only been active since that time (4, 5). However, extensive petroleum exploration in the Subei–South Yellow Sea Basin (Fig. 1) to the north of the modern delta has revealed the stratigraphy of Late Cretaceous–Cenozoic sedimentation, indicating that large fluvial systems must have been feeding the basin since a much earlier time (6). In addition, U–Pb dating of zircons from the modern delta region shows that a river indistinguishable from the modern stream was supplying sediments to that area before 3.2 Ma (7). Further constraints on the initiation of flow come from upstream where the modern Yangtze is controlled by flow through the First Bend (FB) and the Three Gorges (TG; Fig. 1). The age of incision of the Three Gorges has variously been argued to postdate 750 ka (8) at one extreme and to be as early as 40–45 Ma at the other (9). Here we address this debate by study of sediments in the lower reaches of the river in an attempt to determine when the river first achieved its present character.

Geological Setting

Downstream of the Three Gorges, the river crosses the Jianghan Basin (JHB; Fig. 1 and Fig. S1), entering the East China Sea along the southern margin of the Subei–South Yellow Sea Basin. The Jianghan Basin began rifting in the Late Cretaceous, as did the Subei–South Yellow Sea Basin, and became a well-developed extensional basin during the Paleogene (10, 11). Sedimentary sequences, up to 7 km thick and spanning the Late Cretaceous to present, preclude passage of the Yangtze through this region before 36.5 Ma (12). This conclusion is based on the presence of lacustrine and, especially, evaporite sediments (up to 2 km thick) whose depositional age is controlled by well-dated, intercalated volcanic rocks (12, 13). The presence of evaporites and organic-rich lacustrine sediments is incompatible with flow of the Yangtze through that basin at that time because evaporate require a weak supply of water. If the middle and upper Yangtze existed before 36.5 Ma, then they must have drained in a different direction, likely toward the southeast and into the Red River (14–16).

During Neogene time, eastern China entered a postrift phase characterized by thermal subsidence, forming regional downwarping depressions with basin fills onlapping over the earlier fault-bounded rift sequences (6). The Yangtze gravel, which are observed along the lower reaches all of the way from the Three Gorges to the delta, are of fluvial nature and were deposited during this postrift phase.

Basin formation has been linked to volcanic activity, which is tholeiitic and basaltic during the Paleocene–Eocene in northern China, but became more intense in eastern China in the middle to late Miocene when the volcanism switched to alkaline and peralkaline compositions (17). The Yangtze gravel sediments are predominantly sands of fluvial facies and have widely been interpreted as Pleistocene deposits (18), although scattered fossil wood fragments of Miocene age have also been discovered (19). In this study, we examine sections close to Nanjing (Fig. 2 and Dataset S1) where the fluvial sediments are overlain by and interbedded with basaltic lavas that provide the opportunity to accurately date the sediments. Sedimentary sequences underlying the dated basalts were also selected for provenance studies.

40Ar/39Ar Dating of Basalts

The groundmass approach has been widely used to date the rapid cooling young volcanic rocks immediately after their eruption and has been successfully applied worldwide (20), because of the general freshness of young rocks that results in groundmass 40Ar/39Ar ages that are internally concordant and fully consistent with other geological constraints and isotopic methods. Dating of basaltic lavas was performed at the Western Australian Argon Isotope Facility, Department of Applied Geology and John de Laeter Centre, Curtin University, Perth, WA 6845, Australia.

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each sample was step heated in a double vacuum high-frequency Pond Engineering furnace. This approach

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Ages were calculated using the decay constant of Renne et al. (21) and the Fish Canyon sanidine stan-

Mean of all of the plateau steps, each weighted by the inverse uncertainties on the decay constants and the age of the standard

uncertainty of the radiogenic axis (and thus the absence of influence of any minute trapped Ar on the age calculation).

U-Pb Zircon Dating

The sample from Guizishan (Fig. S2A) yielded a complex age spectrum where no straightforward eruption age could be calculated because of the sudden drop in apparent age of three steps in the middle of the spectrum, which was likely caused by late-stage alteration phases. Nevertheless, assuming alteration is the cause of the disturbance, a minimum age can be derived by using all but the three discordant steps in an age spectrum. Because the individual step ages are a mixture between an older crystallization component and a younger alteration component, an absolute age cannot be obtained for this sample. Nonetheless, we can say that the crystallization age must be older than the age given by the flat sections defined by the oldest steps. This yielded a minimum age of 22.9 ± 0.3 Ma (mean square weighted deviation = 1.5; P = 0.16) for the eruption of this lava flow. Samples from Lingyanshan (Fig. S2B) and Xiaopanshan (Fig. S2C) yielded 100% plateau ages of 10.32 ± 0.13 Ma (P = 0.15) and 21.71 ± 0.17 Ma (P = 0.10), respectively, unambiguously indicating the eruption ages of these lava flows, with the 21.7 Ma age being consistent with the 22.9 Ma age from Guizishan. The trapped 40Ar/36Ar compositions of the Guizishan and Xiaopanshan samples (Fig. S2 D and F) are indistinguishable from an atmospheric ratio of ~299 (22) suggesting that no excess 40Ar is present in these samples. No isochron could be obtained for sample Lingyanshan (Fig. S2E) because of a clustering of the data near the radiogenic axis (and thus the absence of influence of any minute trapped Ar on the age calculation).

U-Pb Zircon Dating

Zircon grains from sands in the Yangtze gravels were separated and dated by the U–Pb method to constrain their provenance. This method dates the age at which each zircon crystal cooled below ~750 °C (20) and is a widely used and accepted sediment proxy method based on the concept that different crustal blocks

Isotope Facility at Curtin University, operated by a consortium consisting of Curtin University and the University of Western Australia (Dataset S2). Each sample was step heated in a double vacuum high-frequency Pond Engineering furnace. This approach is designed to look at the gas released from sites of increasing argon retentivity. When a number of consecutive steps, carrying a substantial amount of the total argon released, give the same age, the resulting average value carries geological significance. Plateau ages (Fig. S2) are given at the 2-σ level and are calculated using the mean of all of the plateau steps, each weighted by the inverse variance of their individual analytical error and must define a probability of fit (P) > 0.05. Ages were calculated using the decay constant of Renne et al. (21) and the Fish Canyon sanidine standard for which an age of 28.305 Ma (±0.13%) was adopted. Uncertainties on the decay constants and the age of the standard are not included in the age calculation.

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have different ages of formation and that erosion of the bedrock in a large and diverse drainage basin will result in a unique fingerprint for the zircon age population in any given river. Because of the complexity of the zircon age population in sands from large river basins, samples with identical age populations are likely derived from the same river system eroding the same bedrocks. Because zircon is relatively resistant to abrasion during transport, grains eroded from sources in the headwaters are communicated to the lower reaches. As a result, grains in the catchment, not just those located close to the delta, contribute to the bedload found in the lower reaches. The zircon age spectrum is controlled by the source exposure area and the concentration of zircon in the bedrock (23), although focused erosion may result in certain parts of the basin yielding more sediment than others. The result is that the unique combination of bedrock age, relative abundance, and erosion intensity patterns makes it very unlikely that two large rivers would have the same spectra of zircon U–Pb ages.

The location of the zircon samples within each stratigraphic section are shown in Fig. 2. The sediments are of clear fluvial facies and form cross-bedded sandstone complexes 5 to 10 m thick, which suggests deposition in a significant channel complex. The spectrum of the detrital zircon grain ages (Dataset S3) from each of the considered samples is shown in Fig. 3 using the kernel density estimation (KDE) of Vermeesch (24), which plots the detrital ages as a set of Gaussian distributions, but does not explicitly take into account the analytical uncertainties. Vermeesch argues that this is a more statistically robust method for looking at detrital ages when the number of grains is high and analytical precision are both high. This method allows the age ranges and abundances of the different age populations to be graphically assessed.

Detailed comparison is possible by dividing the zircons up into populations associated with the major tectono-thermal events that have affected the crust of eastern Asia. Specifically we assign grains to groups with the following age ranges: 100–200 Ma (Dabieshan and lower reaches); 200–250 Ma (Indosinian/Qiagntang Block) (25); 400–500 Ma (Songpan Garze) (26); 700–1,000 Ma (Yangtze Craton and Songpan Garze) (27); 1,700–2,100 Ma (Songpan Garze); and 2,400–2,600 Ma (Songpan Garze and North China Craton) (28). We assess the potentially different provenance of each of the sands considered in this study by considering the relative abundance of each of these age groups between different samples. Because individual age ranges are not unique to a single source terrain, and indeed because sources contain grains of different ages, it is not possible to assign individual grain to a single source based only on the U–Pb age, although it is possible to eliminate possible sources. Furthermore, a relatively small number of grains do not fall within these groups, but because little data are lost by removing these and, because these grains are not source diagnostic, they are not helpful in demonstrating how the sediment load of the river has changed through time. We do not try to separate grains associated with the Emeishan flood basin province because the age range of that province is narrow (29) and cannot be unequivocally resolved from the 200–250 Ma range of the Indosinian Orogeny using the inductively coupled plasma mass spectrometry (ICP-MS) method used here. After excluding grains that do not fall within the diagnostic groups the budgets were recalculated to 100% and plotted as pie charts to show the overall character and source of the detrital zircons (Fig. S3). These figures also allow the three age populations younger than 500 Ma to be better resolved into 100–200 Ma (Mesozoic arc magmatism/Yanshanian Orogeny), 200–250 Ma (Indosinian Orogeny), and 400–500 Ma ("Caledonian" Orogeny) (30). As we note above, these age ranges are not unique to single sources, but rather to tectono-thermal events that affected eastern China but which are heterogeneous across the Yangtze drainage basin, so that changes in erosion patterns might be expected to change the age spectrum of the zircon sand grains in the river sediment.

In addition to the modern river and Yangtze gravel samples we plot all of the post–3.2-Ma detrital zircons from the Yangtze Delta (7) in an attempt to provide a general image of the sediment reaching the delta since the Late Pliocene (Fig. 3). Jia et al. (7) have shown that the provenance of the sediment in the area of the modern delta has been approximately constant and similar to the modern river for 3.2 Ma. Our intention is to provide a more time-integrated image of recent flux to the delta because there are moderate variations over short time periods, as demonstrated by the differences between the modern samples from Nanjing and Wuhan that show the river is not of a completely coherent and homogeneous character but that the degree of variation is limited within modest bounds (Fig. 3). Although we accept that provenance can change over different timescales because of changing climatic patterns and evolving rock uplift, it is clear from the work of Jia et al. (7) that the Yangtze has been relatively stable in its provenance, and thus catchment size, for at least 3.2 Ma. This alone is somewhat surprising given the potential influence of the Yellow River in the delta region (Fig. 1).

To test for the influence of the Yellow River we plot zircon U–Pb ages from this system using two samples taken from north of the Qinling-Dabie belt (31) (Fig. 1) and which might reflect the expected composition of the Yangtze gravels if they had actually been deposited from that stream and not the Yangtze River. Two samples are plotted because each is taken at a potential capture point for flow into the Yangtze, and this also allows us to see some of the natural variation within the modern Yellow River. In the recent historical past the lower reaches of the Yellow River have switched between two routes, one in the north to the Bohai Sea (as is the case today) and the other to the south to the Yellow Sea (32). This has led to speculation that a switch of the routes has occurred in the geological history, which would have influenced the sediments of the lower Yangtze system. Fig. 3 shows how the Yellow River age spectra are markedly different from any of the samples taken from the modern and Pleistocene Yangtze River (although they are quite similar to one another), most notably in having a small number of grains dating to 700–1,000 Ma and a high abundance of grains dating to 1,700–2,100 Ma. The complexity of
the zircon age population demonstrates that the Yangtze gravels could not represent the deposits of a locally sourced tributary because this would not have sufficient diversity in its bedrock to generate a complicated age spectrum of this variety.

The pie charts (Fig. S3) represent a simplified version of the KDE diagrams shown in Fig. 3 and are consistent with the visual impression that all of the Yangtze gravel and river samples have similar zircon populations. Not surprisingly the 700–1,000 Ma grains associated with the Yangtze Craton dominate in all these samples. Some variations with time since 23 Ma are to be expected because of active tectonics in the headwaters (32, 33) and changing monsoon intensities since that time, which changes the patterns of erosion within the basin. Nonetheless, it is apparent that all of the Yangtze gravel samples have received zircons from the same array of sources as the modern river and that although the proportion of any particular age group varies, the extent of that variation is limited. We conclude that at least since ~23 Ma, a river similar to the modern Yangtze flowed in the vicinity of Nanjing and that this must have connected to the middle and upper reaches of the present drainage, as the river does today (Fig. 4). The Yangtze gravels are not the product of sedimentation from the Yellow River or a single, local Yangtze tributary, which would be dominated by erosion from the Dabie Shan or rocks dating at 100–200 Ma old granite (34).

To quantify the degree of similarity we here perform additional statistical tests to assess the degree to which the Miocene sediments differ from the modern river at Nanjing, at Wuhan, and from the 3.2-Ma-to-present record at the delta. Statistics suggest that ~100 grains are required to generate a reliable provenance record in a large, complicated drainage like the Yangtze (24). Modern sediments from the Yangtze Delta, not surprisingly, contain zircons from all major source terrains, including some reworked from older sedimentary rocks. We compare that population with the zircon U–Pb ages from the Yangtze gravels and find that there is striking degree of similarity. Kolmogorov–Smirnov (K–S) statistical testing cannot prove that two sands are identical, but it does indicate when there are significant differences between samples. Our analysis (SI Text and Dataset S4) indicates that the Miocene sands are indistinguishable from the modern sediments or from those in the post–3.2-Ma delta, but are different from the Yellow River. We argue that this provides proof of a river flowing through the lower reaches since 23 Ma, and that this stream was collecting sediments from all of the terrains that now feed the Yangtze. The fact that the same age populations can also be seen before 22.9 Ma (Fig. 3) suggests that this river has been in a state of continuous flow from that time until the present day. It appears that the river evolved close to its modern state at least by the Miocene–Oligocene boundary (~24 Ma).

### Drainage Evolution in East Asia

We argue that although sedimentation in the region of the modern delta only dates from the Pliocene (4, 5) this does not preclude an earlier delta located farther north in the Subei–South Yellow Sea Basin. Moreover, an Early Miocene age for the onset of Yangtze River flow is consistent with Nd isotopic data from the Red River system that indicate loss of drainage from the middle Yangtze into that river close to the Oligocene–Miocene boundary (15) (ca. 24 Ma; Fig. 4). Pb isotope characteristics of K-feldspar grains in the Red River delta show a connection with the middle Yangtze in the Eocene, a link that had been lost by the middle Miocene (35), but little firm evidence for a link with the upper reaches of the Yangtze to the Red River. Similarly, U–Pb zircon provenance data from the lower Red River indicates that this river had achieved its present geometry before 12 Ma (36). We follow studies such as Clark et al. (16) in advocating capture and flow reversal of the middle Yangtze (2,140 km between the First Bend and the Three Gorges; ~33% of the total trunk stream length) by connection to the lower reaches before 23 Ma.

It could be argued that the composition of the Yangtze was able to achieve a modern character by 23 Ma as a result of sediment delivery from the Yalongjiang (Fig. 1) rather than from the upper Yangtze, which could still have been connected to the Red River. However, the zircon age spectrum in the sediment in the Yalongjiang is quite different from that at the First Bend on the Yangtze, despite the fact that both rivers have major sources in the Songpan Garze terrane. The Yalongjiang has a very high abundance of 600–1,000 Ma grains compared with the First Bend (76% versus 19%) and is relatively depleted in grains dated at 300–600 Ma and 1,700–2,000 Ma (5% and 3% compared with 23% and 25%; Fig. S3). As a result it is doubtful whether the Yangtze 23 Ma would show the same zircon age spectrum as it does now without a connection to the Yangtze upstream of the First Bend. In any case, data from the Red River itself indicate little definitive evidence for a connection between the Red River and the upper Yangtze at any time (36). In theory there could have been an early Miocene phase with the upper Yangtze connected to the Red River and the Yalongjiang connected to the rest of the Yangtze, although it would be unlikely that the zircon population

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**Fig. 4.** Simplified maps showing the development of the Yangtze River in response to tectonic evolution in East Asia, based on the data presented in this paper as well as associated studies discussed in the text. (A) 32 and (B) 16 Ma. Names of basins as in Fig. 1. Maps reflect the progressive extrusion of Indochina and the opening of the South China Sea, but recognize that the continental blocks east of Longmenshan have remained relatively rigid since the Eocene (59). ASRR, Ailao Shan–Red River Fault; LMS, Longmenshan. Shaded river segment indicates the reversed section of the Yangtze River.
of the Yangtze load would not have been disturbed by the capture of the upper reaches.

Although Richardson et al. (9) favored a connection of the Yangtze through the Three Gorges before 40 Ma, the presence of evaporites in the Jianghan Basin indicates that the exhumation of the Three Gorges at 40–45 Ma could not have been caused by initiation of a throughgoing river flowing in that direction. Although a major river could (and indeed does) flow through a lake system, it is impossible for a lake in the Jianghan Basin to ever become so desiccated that evaporites, with a thickness up to 2 km, would form because this would be inconsistent with significant discharge from the river. Although some rivers may form following a process of alternating fluvial and lacustrine phases, we know that if this process had been operating in the Yangtze it must have ceased before 23 Ma because the provenance observed in the lower reaches requires a fully connected river of the type we see today. A river of this scale is unlikely to be seasonal even during arid climatic conditions, which, in any case are not characteristic of the early and middle Miocene in East Asia (37). Sedimentation rates in the East China Sea show a steady increase during the Oligocene (38), consistent with our model, however there is no sharp jump in accumulation rate, probably because of sediment buffering in depocenters onshore, mostly notably the Jianghan and Subei basins (39).

**Tibetan Tectonics and the Yangtze River**

Birth of the Yangtze River around the start of the Miocene can also be understood in terms of a progressive or stepwise Paleogene uplift of the Tibetan Plateau, because recent paleoaltitude studies support the idea of central and southern Tibet being close to modern elevations no later than the middle Miocene (~16 Ma), rather than indicating a late-stage rapid uplift in the Pleistocene (40).

Although (U–Th)/He thermochronometry from the Longmenshan of western Sichuan indicates that major topographic uplift predated 8–11 Ma (41, 42), a recent study using a variety of thermochronology proxies from this same area indicates significant exhumation starting during the Oligocene–early Miocene and the presence of some topography in eastern Tibet even predating India–Eurasia collision (43). These data are broadly consistent with tectonic models indicating a stepwise growth of the plateau with southeastern Tibet/southwest China uplifting in Oligocene times (44).

Such a late-stage tectonism is strongly affected the geology and topography of the eastern plateau margin and must have been instrumental in helping to guide the reorganization of rivers in the region. The southeastern flank of the Tibetan Plateau is deformed by large strike–slip faults the activity of which is likely linked to the surface uplift. Dating of the Red River fault zone shows that motion started ~34 Ma and was most rapid after 27 and before 17 Ma (45, 46) and other faults in this region (e.g., Xianshui He Fault) share similar ages of motion and exhumation (47, 48). Lacassin et al. (49) note strong shearing and metamorphism of the mountains immediately north of the Yangtze First Bend after 36 Ma, followed by uplift driven by folding around 17 Ma. This date requires that the river was flowing through that region before 17 Ma, although it need not necessarily have been connected to the present day Yangtze. It can be imagined that surface uplift driven by this deformation and related to the progressive growth of Tibetan topography toward the southeast might trigger major reorganization of the rivers flowing through this area and that the initial reorganization of the rivers would occur before major surface uplift (16, 50), i.e., predating 17 Ma.

We emphasize that headwater capture does not require major surface uplift in the First Bend area, but only a gentle rettiling of the topography toward the east, because water will flow downhill even if the slope is not very steep. Indeed, the entrenchment of the Yangtze and its tributaries into deep canyons during the Late Miocene (51) makes further capture after that time very difficult because the topography prevents lateral channel migration. An alternative view is that the Yangtze and other Southeast Asian rivers originated outside the Tibetan Plateau and then cut into this flat, high-standing massif as a result of headward retreat, rather than incising into a low-altitude peneplain that was then uplifted (52). Our data would also be consistent with this model but would require most of the head retreat to be complete by 23 Ma.

If the current geometry of the Yangtze reflects the evolving topography, it is hard to understand how this river could postdate the large-scale late Miocene uplift of eastern Tibet. By dating the Yangtze as being older than 23 Ma we now synthesize our understanding of the river with what is known of topographic growth in the headwaters (Fig. 4). Furthermore, as Tibet continued to grow, sedimentary basins across eastern China experienced the initiation of enhanced early-to-middle Miocene subsidence (53), which are connected by throughgoing fluvial systems, as the case of Jianghan and Subei–South Yellow Sea basins today. Within-plate magmatism testifies to a sharp change in the geodynamic regime at that time, likely linked to rollback of the subducting Pacific plate (54). Initial uplift of Tibet and regional strike–slip faulting driving uplift coupled with subsidence of basins across eastern China opened a path for the Yangtze to the east, diverting the upper and middle reaches away from the Red River and South China Sea.

We further note that the pre-Miocene uplift of the Tibetan Plateau implied by our reconstruction and by recent thermochronology (43) is also consistent with recent revisions concerning the time of intensification of the East Asian summer monsoon close to the start of the Miocene (37, 55) rather than during the late Miocene ~8 Ma as had previously been believed (56). These new dates for monsoon strengthening are based on environmental and floral proxies and are not model dependent and more closely linked to precipitation than had been the case for earlier monsoon indicators. Prell and Kutzbach (57) are among several studies that predict a correlation between increasing plateau altitude and monsoon intensity. Although it is clear that monsoon intensity is controlled by more than simply Tibetan elevation, recent climate models still show that the presence of a plateau intensifies summer rainfall in the Asian region (58). Thus, the timescale of uplift implied by the start of Yangtze throughflow before 23 Ma is consistent with the more recent climate reconstructions that indicate strengthening around the end of the Oligocene (37, 55).

**Conclusions**

In this study we constrain the age of initiation of the Yangtze River through study of the Yangtze gravels in the region of Nanjing. The 40Ar/39Ar dating of basalt interbedded within these sediments shows that some of these were deposited before 23 Ma, and are not Pleistocene as previously assumed. We further analyzed the provenance of the gravels through application of U–Pb dating to zircon sand grains extracted from these deposits. Statistical analysis shows that lower Miocene sediments are indistinguishable from sediments collected from the modern river or from the delta during the last 3.2 Ma. This requires that a river, much like the modern one, was in existence before 23 Ma. Our data do not allow us to date the oldest possible age of the Yangtze, but we infer that the river did not start before the late Eocene because of the presence of evaporites in the Jianghan Basin before that time. Those sediments lie just downstream of the Three Gorges and preclude major river flow until after 36.5 Ma. A pre–23-Ma Yangtze River is consistent with both recent estimates for the timing of eastern Tibetan uplift, the onset of major strike–slip deformation, and with the age of headwater capture of the middle Yangtze reaches away from the Red River. Our study confirms a close relationship between the evolving tectonically driven topography and drainage systems in East Asia during the Cenozoic.
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