



PERSPECTIVES

ANTHROPOLOGY

Emperor Yu's Great Flood

Geological data provide support for a legendary flood in China ~4000 years ago

By David R. Montgomery

We know of the legendary Emperor Yu through the story of China's Great Flood, a tale already ancient when first recorded around 1000 BCE (1). On page 579 of this issue, Wu *et al.* offer a provocative new explanation for this story. They present evidence for an enormous landslide dam break 1922 ± 28 BCE (2) that coincided

with the major cultural transition from the Late Neolithic to the Early Bronze Age in China and that also helps explain curious details of Yu's story.

According to folk tradition, the story of Yu's Great Flood is an oral history of real disaster, handed down for a millennium before entering written records. However, in the absence of geological evidence for such a flood, some scholars have argued that the story is either a historicized version of an

older myth or propaganda to justify the centralized power of imperial rule (1, 3).

In contrast to the hero of another well-known flood story, Yu is not heralded for surviving a great deluge sent by an angry god. Rather, the story tells of how he directed efforts to dredge and channel rivers to drain the floodwaters (3). It casts this

Earth and Space Sciences, University of Washington, Seattle, WA 98195, USA. Email: bigdirt@uw.edu

Battling the Great Flood. Emperor Yu's fantastical achievements include defeating the dragon that stirred up the Great Flood and ridding the floodwaters of serpents and dragons that drove off settlers.

triumph of human ingenuity as bringing order to the land so that fields could be planted, thereby setting the stage for the lowland agriculture that fueled the blossoming of Chinese civilization. A telling aspect of the story—that it took Yu and his followers decades to control the floodwaters—makes sense in light of the geological evidence that Wu *et al.* present.

Wu *et al.* report that an ancient landslide dammed the Yellow River in the Jishi Gorge on the edge of the Tibetan Plateau. Through mapping and dating lake sediments impounded behind the dam and also distinctive sediments deposited downstream, the authors show that an enormous flood surged down the river when the dam broke. They find that this flood coincided with the social disruption of a major cultural transition and suggest that it breached the river's natural levees. The timing of the flood, Wu *et al.* report, coincides with an avulsion that redirected the Yellow River to carve a new course across the North China Plain about 2000 BCE (2). It would have taken considerable time for a large river to adjust to such a change, and the associated sustained flooding would fall in the right time and place to account for Yu's story—including the long time it took to control the floodwaters.

This support for the historicity of Yu's flood is part of a broader pattern, another piece in long-standing debates over stories of epic deluges. These stories have been particularly contentious in the Western world. After all, attempts to explain the biblical story of Noah's Flood not only shaped the early development of geology but later fueled discoveries refuting the biblically inspired idea that a global flood laid down the world's sedimentary rocks in the first place (4). But how many of these ancient stories might actually record regional flood disasters?

A century ago, the Scottish anthropologist James Frazer detected a pattern in flood stories from around the world (5). In case after case across cultures, stories of great floods evoked descriptions of local natural events. A rising sea was the cause of floods in stories from Pacific islands prone to huge earthquake-generated waves (tsunamis). Many Native American stories along the Cascadia subduction zone, from

Northern California to British Columbia, also describe floods coming from the sea (6). They tell of ancient fights between Thunderbird and Whale so violent that they caused the ground to shake and triggered huge waves, killing scores and lodging canoes in treetops. Indeed, stories from across the tsunami-prone Pacific—from Indonesia to Chile—tell of surprise floods from the sea.

In contrast, stories from regions with formerly more extensive glaciers, such as Scandinavia, Tibet, and North America, evoke failure of glacial dams as the cause of great floods (4). Another recurring theme is lowland flooding. For example, Ryan and Pitman have argued that the story of Noah's Flood describes how a rising Mediterranean Sea spilled into a low-lying freshwater valley to create the Black Sea (7). Another potential explanation for Noah's Flood updates the idea of levee failures inundating low-lying terrain along the Tigris and Euphrates rivers (4), in light of catastrophic flooding during Cyclone Nargis in 2008, when more than 130,000 people were killed in Myanmar's Irrawaddy delta (8). It increasingly seems that fundamental elements of the global tapestry of great flood stories mirror the geography of tsunamis, glacial outburst floods, and catastrophic lowland flooding.

Great floods occupy a central place in some of the world's oldest stories. And Emperor Yu's flood now stands as another such story potentially rooted in geological events. Time and again, natural disasters like great floods, earthquakes, and volcanic eruptions inspired tales passed down through generations and civilizations to become legends (4, 9). How many other ancient stories of intriguing disasters might just have more than a grain of truth to them? ■

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PHYSICS

Bringing order to the expanding fermion zoo

Crystallographic classification provides an inventory of the electron-like particles that emerge in a lattice world

By Carlo Beenakker

We observe space as a continuum, but we might entertain the thought that there is an underlying lattice and that space is actually a crystal. Which particles would inhabit such a lattice world? This question was first raised by Werner Heisenberg in 1930 in an attempt to remove the infinities that plagued the continuum quantum mechanics. His *Gitterwelt* (lattice world) hosted electrons that could morph into protons, photons that were not massless, and more peculiarities that compelled him to abandon “this completely crazy idea” (1, 2). Heisenberg's motivation to put electrons on a lattice came from solid-state physics, which in the 1930s was just developing as a field of research and which has now become a playground for “crazy ideas” from particle physics. In this spirit, on page 558 of this issue Bradlyn *et al.* (3) use concepts borrowed from crystallography to classify the electronic excitations of the lattice world, and then use that to identify possible candidates of materials where they become a reality as (nonfundamental) quasiparticles.

The idea that electrons on a lattice might turn into altogether different quasiparticles was forcefully demonstrated in graphene: An electron moving on the two-dimensional honeycomb lattice of carbon atoms loses its mass. In the language of particle physics, the electron is said to have been transformed from a massive Dirac fermion into a massless Weyl fermion. If the lattice

Instituut-Lorentz, Leiden University, 2300 RA Leiden, Netherlands. Email: beenakker@lorentz.leidenuniv.nl

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Emperor Yu's Great Flood

David R. Montgomery (August 4, 2016)

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Editor's Summary

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The projected states are composed of two sublattice components in the emitter and collector. As a result, momentum-dependent constructive ($\varphi_{e(c)} = 0$) or destructive ($\varphi_{e(c)} = \pi$) interference between sublattice components is governed by $|\psi_A + \psi_B|^2 \propto 1 + \cos\varphi_{e(c)}$, for the states both in emitter (φ_e) and collector (φ_c) and manifests itself in the tunneling characteristics ($I(V_b)$). Because the magnetic field selects the pairs of particular plane wave states probed by tunneling at a particular gate or bias voltage (Fig. 4, A and B), the measured asymmetry provides a direct visualization of the pseudospin polarization of the Dirac fermions.

In the presence of the magnetic field, each resonance peak represents tunneling from a particular corner of the BZ. This allows one to inject electrons with a particular valley polarization, and from a selected corner of the BZ. We use the experimental parameters to calculate the amount of polarization achieved in our experiment (Fig. 3, J and M), and estimate that the valley polarization, $P = (I_K - I_{K'}) / (I_K + I_{K'})$ [where $I_K (I_{K'})$ is the current injected into the K(K') valley] can be as high as 30% (40%) for the particular Gr/3hBN/Gr (Gr/5hBN/BGr) devices. The main limit to the degree of polarization is the energy broadening of states at the Fermi levels caused by inelastic tunneling processes. However, even for the current level of disorder, with the resonances at around $V_b \approx 0$ V (e.g., resonances marked by yellow dashed lines on Fig. 2D at $V_g > 50$ V), which maximizes the number of states participating in tunneling and sensitive to magnetic field, a polarization close to 75% could be achieved (19). By using devices with smaller misalignment between the graphene electrodes [on the order of 0.2° , now within the reach of the current technology (19)], valley polarization close to 100% is possible (19).

The same mechanism can also be used to select electrons with a particular pseudospin polarization. In Fig. 4, C to R, we present results of a calculation of the contribution of different electronic states in k -space to the tunnel current for the Gr/3hBN/Gr (Fig. 4, C to I) and Gr/5hBN/BGr (Fig. 4, J to R) devices. We choose the position of the Fermi levels in the emitter and collector to be very close to a resonance at $B = 0$ T. Then, for certain directions of B , the resonant conditions are achieved only in one valley and for only a very narrow distribution in k -space (Fig. 4, G to I). Tunneling of the electrons from other parts of k -space is prohibited either because they are off-resonance or because of the pseudospin selection rule. Alternatively, for the Gr/5hBN/BGr device and exploiting the difference in curvature of monolayer and bilayer electronic bands, we can choose the overlap between the bands in such a way that the magnetic field reduces the overlap in one valley and increases it for the other (Fig. 4, M to R). In this case, momentum conservation at $B = 0$ T is fulfilled for the states marked by white dashed lines (Fig. 4O). However, only one of those lines contributes to tunneling, owing to pseudospin interference (Fig. 4, M and N).

Our technique, which enables tunneling of valley-polarized electrons in monolayer and bilayer gra-

phene, also allows one to selectively inject carriers propagating in the same direction and to probe pseudospin-polarized quasi-particles. In principle, the technique can be extended to tunneling devices in which surface states of topological insulators are used as electrodes; then, all-electrical injection of spin-polarized current (28) with non-invasive tunneling contacts could reveal a number of exciting phenomena (29–31).

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SUPPLEMENTARY MATERIALS

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ARCHAEOLOGY

Outburst flood at 1920 BCE supports historicity of China's Great Flood and the Xia dynasty

Qinglong Wu,^{1,2,3,*†} Zhijun Zhao,^{2,13} Li Liu,^{4,†} Darryl E. Granger,⁵ Hui Wang,⁶ David J. Cohen,^{7,†} Xiaohong Wu,¹ Maolin Ye,⁶ Ofer Bar-Yosef,⁸ Bin Lu,⁹ Jin Zhang,¹⁰ Peizhen Zhang,^{3,14,§} Daoyang Yuan,¹¹ Wuyun Qi,⁶ Linhai Cai,¹² Shibiao Bai^{2,13}

China's historiographical traditions tell of the successful control of a Great Flood leading to the establishment of the Xia dynasty and the beginning of civilization. However, the historicity of the flood and Xia remain controversial. Here, we reconstruct an earthquake-induced landslide dam outburst flood on the Yellow River about 1920 BCE that ranks as one of the largest freshwater floods of the Holocene and could account for the Great Flood. This would place the beginning of Xia at ~1900 BCE, several centuries later than traditionally thought. This date coincides with the major transition from the Neolithic to Bronze Age in the Yellow River valley and supports hypotheses that the primary state-level society of the Erlitou culture is an archaeological manifestation of the Xia dynasty.

China's earliest historiographies, including *Shujing* (*Book of Documents*) and *Shiji* (*Records of the Grand Historian*), by Sima Qian, tell of the Great Flood, a lengthy, devastating flood of the Yellow

River. The culture hero Yu eventually tamed this flood by dredging, earning him the divine mandate to establish the Xia dynasty, the first in Chinese history, and marking the beginning of Chinese civilization. Because these accounts laid

the ideological foundations for the Confucian rulership system, they had been taken as truth for more than 2500 years until challenged by the “Doubting Antiquity School” in the 1920s. Within a decade, archaeological excavations demonstrated the historicity of the second dynasty, Shang, and the search for similar evidence for Xia began (1, 2). Archaeological fieldwork since the 1950s on the Early Bronze Age Erlitou culture (~1900 to 1500 BCE) has led many scholars to associate it with the Xia (1–6) because it overlaps with the spatial and temporal framework of the Xia dynasty. Traditionally, historians have dated the start of Xia to ~2200 BCE, whereas the government-sponsored Xia-Shang-Zhou Chronology Project adopted the date as 2070 BCE (5), leaving a chronological gap in associating Erlitou with Xia (7–9). Other scholars see Xia purely as a myth fabricated to justify political succession (10, 11).

Scholars also have long sought a scientific explanation of the Great Flood (12–14), with even Lyell mentioning it (15), yet no evidence for it has been discovered. Here, we present geological evidence for a catastrophic flood in the early second millennium BCE and suggest that it may be the basis of the Great Flood, thereby lending support to the historicity of the Xia dynasty. The evidence found in our investigations along the Yellow River in Qinghai Province includes remains of a landslide dam, dammed lake sediments (DLS) upstream, and outburst flood sediments (OFS) downstream (Fig. 1 and figs. S1 to S5) that allow us to reconstruct the size of the lake and flood (16).

Field observations (fig. S2B) show that the ancient landslide dam deposits reach an elevation of 240 m above present river level (arl) and stretch for 1300 m (fig. S2A) along Jishi Gorge (Figs. 1A and 3A). We estimate that the saddle of the dam would have been 30 to 55 m lower than the highest preserved remnants, so

the lake would have filled to an elevation of 185 to 210 arl [2000 to 2025 m above sea level (asl)] (fig. S2B), impounding 12 to 17 km³ of water (16) (table S1). Based on typical river discharge values, the dam would have completely blocked the Yellow River for 6 to 9 months before overtopping (16). DLS distributed widely upstream of the dam are up to 30 m thick and have a highest elevation of ~1890 m asl (Fig. 1B and figs. S1 and S3A). We interpret this as indicating that the catastrophic breach dropped the water level 110 to 135 m (Fig. 1B), releasing ~11.3 to 16 km³ of water (16) (table S1), tens of times that estimated by a previous study (17). After the breach, DLS infilled a residual lake behind the lowest part of the dam that remained.

Outburst flood sediments are found downstream at elevations from 7 to 50 m arl in the lower Jishi Gorge and in Guanting Basin (Fig. 1 and figs. S1 and S4). They are characterized by high-concentration suspension deposition and consist exclusively of angular clasts of greenschist and purple-brown mudrock sourced from Jishi Gorge (table S2). At the mouth of the gorge, where the Yellow River enters Guanting Basin, the sediments reach 20 m thickness and include boulders up to 2 m in diameter (Fig. 1B and figs. S1 and S4, C and D). We also identified the OFS at the earthquake-destroyed prehistoric Lajia site (fig.

S5), a settlement of the Qijia culture (18, 19) known for its early noodle remains (20), 25 km downstream from the dam. OFS at Lajia covered the settlement's last Qijia culture occupation and filled in collapsed cave dwellings (fig. S5, A and B), pottery vessels (fig. S5B), and earthquake fissures (fig. S5C), mixing with pottery sherds (fig. S5D) and other Qijia cultural materials, with heights of up to 38 m arl.

Stratigraphic relationships of the OFS, remnant dam, DLS, loess, and other deposits in Jishi Gorge and neighboring basins, along with destruction features at the Lajia site (fig. S1), allow us to reconstruct and date a sequence of events ending in the outburst flood. First, they show that the damming and outburst flood event occurred during the archaeological Qijia culture period (~2300 to 1500 BCE) after the collapse of the Lajia cave-houses. Ground fissures caused by the earthquake at the Lajia site were entirely filled with OFS (fig. S5C) before silts from surface runoff during the annual rains could enter them, indicating that the outbreak flood must have occurred less than 1 year after the earthquake and collapse of the houses. It is likely that the same earthquake that destroyed Lajia also triggered the landslide that dammed the river, along with widespread contemporaneous rock avalanches whose deposits lay directly beneath the DLS (fig. S3A).

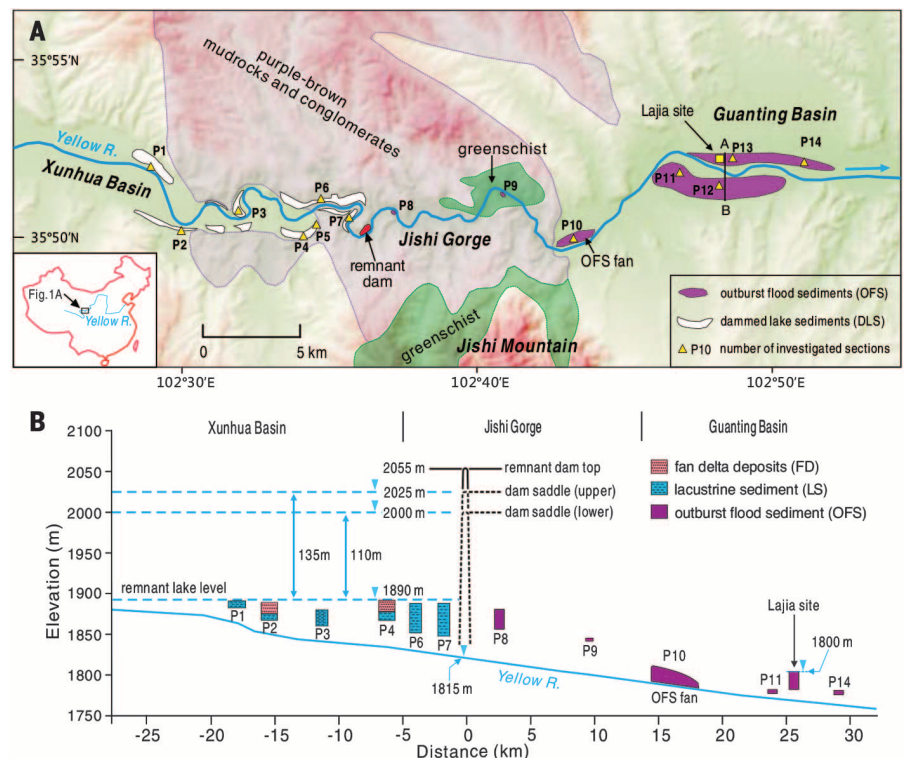


Fig. 1. Evidence of the exceptional outburst flood in the upper valley of the Yellow River. (A) Distributions of OFS, DLS, and landslide dam. Light purple and dark green shaded areas indicate purple-brown mudrock and greenschist, respectively. Line AB across the Lajia site shows the location of the reconstructed cross section in fig. S6C. **(B)** The vertical distribution of the OFS, landslide dam, DLS, Lajia site and reconstructed lake levels relative to the longitudinal profile of the present Yellow River. DLS are classified into lacustrine sediments (LS) and fan delta deposits (FD).

¹School of Archaeology and Museology, Peking University, Beijing 100871, China. ²School of Geography Science, Nanjing Normal University, Nanjing 210023, China. ³State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing 100029, China. ⁴Department of East Asian Languages and Cultures, Stanford University, Stanford, CA 94305, USA. ⁵Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN 47907, USA. ⁶Institute of Archaeology, Chinese Academy of Social Sciences, Beijing 100710, China. ⁷Department of Anthropology, National Taiwan University, Taipei 10617, Taiwan (R.O.C.). ⁸Department of Anthropology, Harvard University, Cambridge, MA 02138, USA. ⁹CCTEG Xi'an Research Institute, Xi'an 710077, China. ¹⁰Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China. ¹¹Lanzhou Institute of Seismology, China Earthquake Administration, Lanzhou 730000, China. ¹²Qinghai Provincial Institute of Cultural Relics and Archaeology, Xining 810007, China. ¹³Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing, Jiangsu 210023, China. ¹⁴School of Earth Science and Geological Engineering, Sun Yat-sen University, Guangzhou 510275, China.

*Corresponding author. Email: wuqinglong@pku.edu.cn

†Present address: School of Geography Science, Nanjing Normal University, Nanjing 210023, China. ‡These authors contributed equally to this work. §Present address: School of Earth Science and Geological Engineering, Sun Yat-sen University, Guangzhou 510275, China.

To date the outburst flood, we collected carbon samples for accelerator mass spectrometry (AMS) ^{14}C dating (16). Seventeen charcoal samples from the OFS and the only charcoal sample from a layer overlying the OFS (fig. S1) indicate that the age for the flood is between 2129 and 1770 cal. BCE [95% confidence interval (CI)] (Fig. 2A and table S5) (16). Charcoal samples from DLS upstream of the dam (fig. S1) yield calibrated ^{14}C results (95% CI) spanning 2020 to 1506 BCE (Fig. 2A and table S5), demonstrating that the DLS is coeval with or younger than the outburst flood and confirming that it is fill from the remnant lake. The best dating for the flood comes from the Lajia site (16), because it was destroyed within 1 year before the outburst flood. Radiocarbon determinations of bone samples from three human victims, aged 6 to 13 years old, in collapsed Lajia dwellings (Fig. 2B) agree to within uncertainty (Fig. 2A and table S5), consistent with that of two victims reported previously (21) as well. Because the radiocarbon calibration curve is linear in this region and the bones are the same age, we use the inverse variance weighted mean of the three measurements. This yields a calibrated age with a median of 1922 ± 28 BCE (1 SD) and a 95% CI of 1976 to 1882 BCE (Fig. 2C). To simplify this range, we use 1920 BCE to indicate the approximate date of the flood.

We estimate the peak discharge of the flood in two ways. Empirical formulas considering the volume of the lake and the height of the dam lead to estimates ranging from 0.08 to $0.51 \times 10^6 \text{ m}^3 \text{ s}^{-1}$, with large uncertainties (16)

(table S3). We also reconstruct the flood channel cross section from detailed surveys in Guanting Basin and use Manning's equation to estimate a peak discharge of 0.36 to $0.48 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ (16) (fig. S6 and table S4), consistent with the dam break estimations (16) (table S3). The calculated peak discharge of $\sim 0.4 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ is more than 500 times the average discharge of the Yellow River at Jishi Gorge. This ranks globally among the largest freshwater floods of the Holocene (22).

We do not explicitly model the inundation and effect of this outburst flood in the lower reaches of the river, but analogous events demonstrate that outburst floods from landslide dams can propagate long distances. In 1967, an outburst flood with a volume of just $\sim 0.64 \text{ km}^3$ propagated at least 1000 km along the Yalong-Yangtze Rivers (23), so the Jishi prehistoric outburst flood, with a volume of ~ 11 to 16 km^3 , could have easily travelled more than 2000 km downstream. The Jishi flood would have breached the natural levees of the Yellow River, resulting in rare, extensive flooding. It is possible that this outburst flood was also the cause of a major avulsion of the lower Yellow River (Fig. 3A) inferred from archaeological data, with a previously estimated date of ~ 2000 BCE (24, 25). Widespread destruction of levees and deposition of tributary mouth bars may have destabilized the main river channel, leading to repeated flooding until a new river channel was established. Extensive flooding on the lower Yellow River plain would have had a great effect on societies there. We argue that this event and its aftermath likely would have sur-

vived in the collective memories of these societies for generations, eventually becoming formalized in the received accounts of the Great Flood in the first millennium BCE. In fact, early texts such as the *Shujing* and *Shiji* even record that a place called Jishi (the same characters as the gorge where the outburst flood began) was where Yu began his dredging of the Yellow River; whether this is a coincidence will require further historical geographical research.

The ~ 1920 BCE flood shares the main characteristics of the Great Flood described in ancient texts. Apart from its huge peak discharge, the secondary flooding on the lower plains may have been long-lasting, just as the Great Flood remained uncontrolled for 22 years until it was managed by dredging (rather than by blocking breaches in natural levees). There is also the issue of whether the Great Flood could have been caused by exceptional meteorological flooding, but a speleothem record shows a generally weakened Asian summer monsoon from 8000 to 500 years before the present (26), and proxies from lake and loess records also indicate that a cool, dry climate regime begins 2000 BCE along the lower Yellow River (27), so this would be unlikely. Furthermore, the early textual records make no mention of frequent, extreme storms related to the Great Flood.

The discovery and reconstruction here of the massive outburst flood originating in Jishi Gorge provide scientific support that the ancient Chinese textual accounts of the Great Flood may well be rooted in a historic natural event. They also shed light on the potential

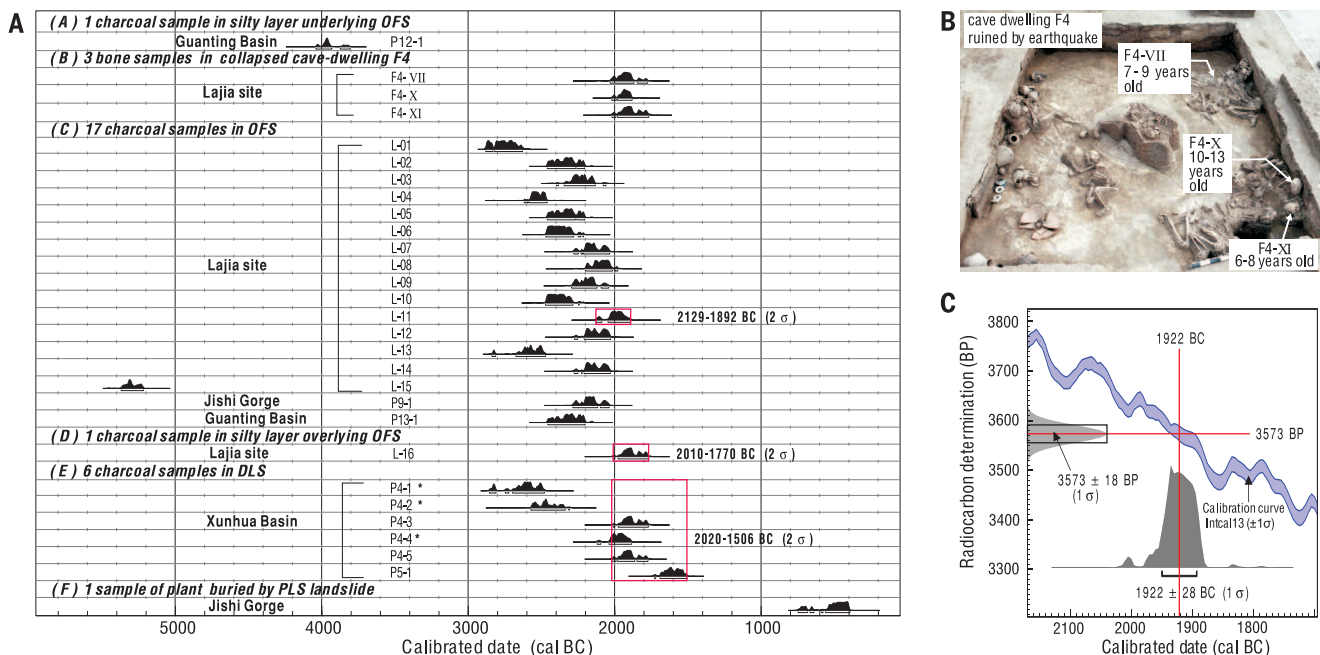


Fig. 2. Radiocarbon chronology of the prehistoric outburst flood on the Yellow River. (A) Calibrated age probabilistic histograms of radiocarbon data. The outliers of the ages inconsistent with stratigraphic sequences and indicating reworking are denoted with asterisks. Samples best constraining the age of the outburst flood are boxed in red. See fig. S1 for sample locations. (B) The radiocarbon dated skeletons in cave dwelling F4 at the Lajia site. The skeletons were identified by reference (30). (C) The calibration of the inverse variance weighted mean for three bone samples on calibration curve IntCal13 (31). All radiocarbon dates were calibrated individually with IntCal13 (31) and OxCal 4.2 (32).

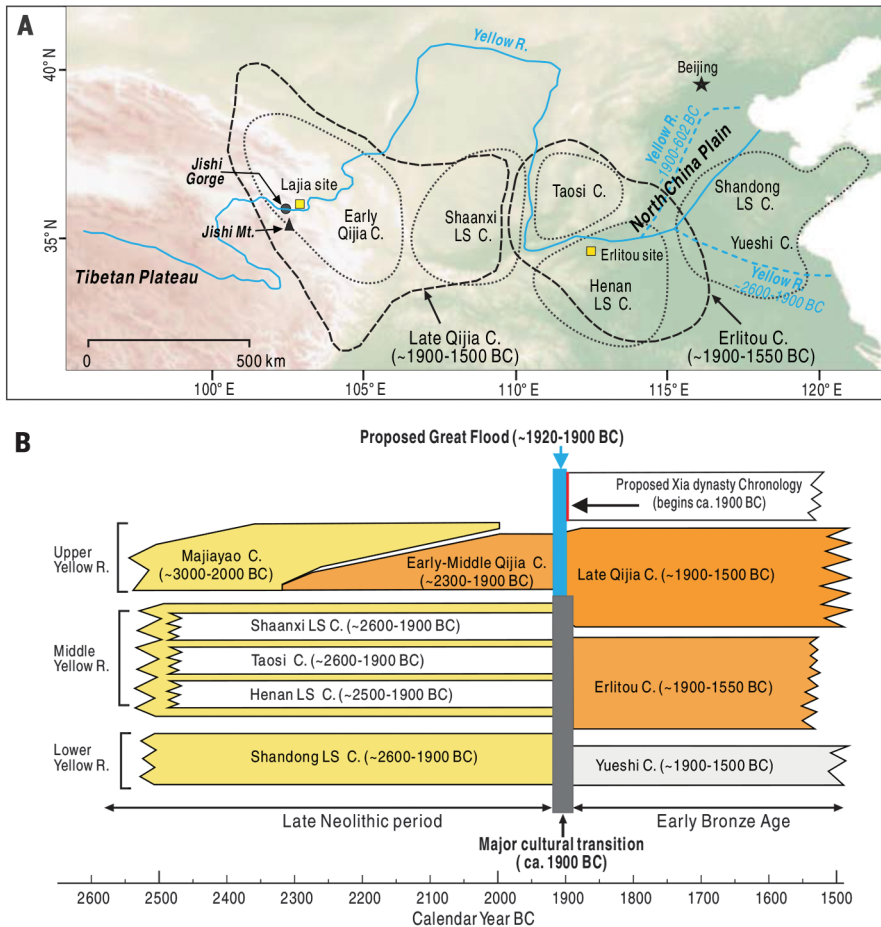


Fig. 3. Major transition of archaeological cultures in the Yellow River valley around 1900 BCE. C, culture; LS C, Longshan culture. (A) Distribution of the late Neolithic and early Bronze Age cultures in the Yellow River valley. Blue dashed lines show avulsion of the lower Yellow River channel ~2000 BCE (24). (B) Timeline showing early ages of the archaeological cultures (6, 29) and the proposed Great Flood of China.

historicity of the Xia dynasty itself, as Yu's founding of the dynasty is directly tied to his achievements in controlling the Great Flood. According to the *Shiji*, Yu's father labored unsuccessfully for 9 years to tame the flood before Yu took over for 13 more years. Yu's success led to his mandate to become founding king of the Xia 22 years after the flood started. If the Jishi Gorge outburst flood of ~1920 BCE is the natural cataclysm that came to be known as the Great Flood, then we can propose a new beginning date for the Xia dynasty, ~1900 BCE. This date, some 2 to 3 centuries later than previous reckonings (1, 2, 5), is compatible with the 1914 BCE date proposed by Nivison based on astro-historiographical evidence (28). This 1900 BCE date for the founding of the Xia coincides with the beginning of the Erlitou culture (6), so this finding also supports the arguments that the Erlitou culture is the archaeological manifestation of the Xia and that the Erlitou site was a Xia dynastic capital (1-3). This outburst flood is

also coincident with the major sociopolitical transition from Neolithic to Bronze Age in the Yellow River valley (2, 6, 29) (Fig. 3, A and B), suggesting that the concurrence of these major natural and sociopolitical events known through the geological, historiographical, and archaeological records may not simply be coincidence but rather an illustration of a profound and complicated cultural response to an extreme natural disaster that connected many groups living along the Yellow River.

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SUPPLEMENTARY MATERIALS

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Outburst flood at 1920 BCE supports historicity of China's Great Flood and the Xia dynasty

Qinglong Wu, Zhijun Zhao, Li Liu, Darryl E. Granger, Hui Wang, David J. Cohen, Xiaohong Wu, Maolin Ye, Ofer Bar-Yosef, Bin Lu, Jin Zhang, Peizhen Zhang, Daoyang Yuan, Wuyun Qi, Linhai Cai and Shibiao Bai (August 4, 2016)
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Editor's Summary

Flood control initiates Chinese civilization

Around four millennia ago, Emperor Yu the Great succeeded in controlling a huge flood in the Yellow River basin. This is considered to have led to the establishment of the Xia dynasty and the start of Chinese civilization. However, the dates of the events and the links between them have remained uncertain and controversial. Using stratigraphic data and radiocarbon dating, Wu *et al.* verify that the flood occurred and place the start of the Xia dynasty at about 1900 BC, thus reconciling the historical and archaeological chronologies (see the Perspective by Montgomery).

Science, this issue p. 579; see also p. 538

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