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Great flood in the middle-lower Yellow River reaches at 4000 a BP inferred from accurately-dated stalagmite records

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Recently, Wu et al. [1] suggested an earthquake-induced landslide dam outburst flood on the eastern Tibetan Plateau at 1920 BCE (3870 a BP, BP denotes year before 1950 CE) caused the Great Flood in the middle-lower Yellow River reaches, and resulted in the founding of Xia Dynasty at 3850 a BP. This age is ~150–300 younger than the previously estimated age of the Xia Dynasty [2]. While the geological evidence of the outburst flood, including its date is in debate [3,4], how a dam failure in the eastern Tibetan Plateau could cause great flood 2000 km downstream was also questioned [5,6]. Here we provide highly-resolved, absolutely-dated stalagmite evidence from the Loess Plateau (LP) for extreme rainfall event and probably great flood in the middle-lower Yellow River reaches at about 4000 a BP.

Wuya Cave (33°49′14″ N, 105°25′35″ E, 1370 m above sea level) is located on the southwestern margin of the LP, Gansu Province, China [7]. Four columnar stalagmites, WY12, WY27, WY33, and WY56 were collected inside the cave 500–700 m away from the entrance in 2011. WY27 and WY33 are annually-layered stalagmites and were actively growing when collected. According to the layer counting chronologies, WY27 and WY33 grew from 309 to −60 a BP and 201 to −60 a BP respectively [7]. ^{230}Th dating results (Table 1) indicated that WY56 deposited between 813 and 1441 a BP and WY12 formed between 2692 and 6230 a BP with a hiatus during 4625–5000 a BP (Fig. 1a).

Stalagmites WY27 and WY33 show similar decadal-scale δ^{18}O variations during the contemporaneous period (Fig. 1b), suggesting possible isotopic equilibrium depositions [10]. Both geological and simulation results suggested that speleothem δ^{18}O records from northern China can represent the Asian monsoon intensity and local monsoon rainfall amount, with negative δ^{18}O values representing enhanced monsoon intensity and regional monsoon rainfall in northern China [11–13]. Indeed, a significant negative correlation between the δ^{18}O of WY33 and local rainfall amount ($r = -0.44$, $P < 0.01$) were observed during the last 60 years [7]. Spatial correlation analyses further indicate that the regional rainfall variations and the whole LP are positively correlated [7]. As a result, the stalagmite δ^{118}O record from Wuya Cave could be used as a reliable indicator of rainfall changes on the LP, with lower stalagmite δ^{118}O values representing higher rainfall and *vice versa*.

As shown in Fig. 1a, there is a general decreasing trend of monsoon rainfall on the LP during 4500–3500 a BP. Three extreme pluvial intervals were observed with their peaks occurred at ~4200, ~3996, and ~3677 a BP respectively. Recent observations suggested that the precipitation changes on the LP, the main sediment source and water-catchment area of the Yellow River [14], are critical to the water and life securities over the middle-lower Yellow River reaches. Indeed, runoff changes of the middle Yellow River [8] match the stalagmite-inferred precipitation data very well during the past 238 years (1766–2004 CE) with a significant correlation coefficient of −0.33 ($P < 0.01$, 5 years smoothing of WY33 δ^{18}O series and runoff record) (Fig. 1b and c). The extreme rainfall on the LP had caused three most severe outburst floods of the middle-lower Yellow River over the past 200 years, which occurred in 1841–1843, 1855, and 1887 CE [9]. The flood caused catastrophic damage to the society. For example, historical book recorded that the outburst flood of 1841–1843 affected the whole northern China and killed millions of people [9].

The stalagmite δ^{18}O values at ~4200, ~3996, ~3677 a BP all exceeded those when the megafloods occurred during the last 200 years, indicating enhanced rainfall and probably severe floods during these times. The ages of these extreme rainfall events are robust with nine precise ^{230}Th dating control points during 4500–3500 a BP (Table 1). For example, two ^{230}Th dates, 3930 ± 37 and 4016 ± 48 a BP, anchor the age of the extreme event at 3996 a BP. Two more dates of 4161 ± 42 and 4249 ± 75 a BP spike the 4200 a BP event. Previous archeological and historical studies suggested that the initial age of China's Xia Dynasty was in the range of ~1900–2200 BCE (3940–4150 a BP) [2]. Both extreme rainfall/flood events at ~4000 a BP and ~4200 a BP with uncertainties of few decades are within the possible age range of the start of Xia Dynasty [15]. In particular, the age determined at 4000 ± 48 a BP exactly matches the government-sponsored Xia-Shang-Zhou Chronology Project estimated date of 2070 BCE (4020 a BP) [15]. This agreement, to some extent, supports the historicity of the Great Flood and the Xia Dynasty.

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Table 1
U-Th dating results of WY12 and WY56.

Sample Number	^{238}U (ppb)	^{232}Th (ppt)	^{230}Th/^{232}Th (atomic × 10^{-6})	δ^{234}U* (measured)	^{230}Th/^{238}U (activity)	^{230}Th Age (a) (uncorrected)	^{230}Th Age (a BP)*** (corrected)	$\delta^{234}U_{initial}^{**}$ (corrected)
WY12-0.5	257 ± 0.6	2253 ± 46	98 ± 3	971.8 ± 3.3	0.0521 ± 0.0008	2915 ± 47	**2725 ± 103**	979 ± 3
WY12-3	315 ± 0.6	1376 ± 28	207 ± 4	958.0 ± 3.5	0.0547 ± 0.0003	3082 ± 18	**2958 ± 49**	966 ± 4
WY12-10	319 ± 0.7	599 ± 10	506 ± 9	975.3 ± 4.6	0.0576 ± 0.0004	3219 ± 25	**3128 ± 28**	984 ± 5
WY12-20	319 ± 1.2	278 ± 12	1160 ± 53	953.9 ± 8.3	0.0614 ± 0.0005	3471 ± 34	**3393 ± 34**	963 ± 8
WY12-23	320 ± 1.3	349 ± 12	968 ± 34	945.5 ± 9.0	0.0641 ± 0.0006	3643 ± 38	**3562 ± 39**	955 ± 9
WY12-26	396 ± 1.5	387 ± 9	1084 ± 27	940.9 ± 8.2	0.0643 ± 0.0005	3667 ± 31	**3588 ± 31**	951 ± 8
WY12-34	311 ± 1.0	475 ± 11	722 ± 18	950.1 ± 6.8	0.0669 ± 0.0005	3795 ± 33	**3708 ± 35**	960 ± 7
WY12-39	283 ± 1.1	1488 ± 10	217 ± 2	937.0 ± 8.3	0.0693 ± 0.0006	3961 ± 37	**3824 ± 51**	947 ± 8
WY12-42	262 ± 1.0	356 ± 7	850 ± 19	936.8 ± 8.4	0.0702 ± 0.0005	4014 ± 36	**3930 ± 37**	947 ± 8
WY12-50	239 ± 0.7	363 ± 11	776 ± 24	927.2 ± 6.4	0.0714 ± 0.0008	4103 ± 46	**4016 ± 48**	938 ± 6
WY12-54	238 ± 0.8	673 ± 10	430 ± 7	918.6 ± 6.7	0.0738 ± 0.0006	4266 ± 37	**4161 ± 42**	930 ± 7
WY12-60	209 ± 0.8	1793 ± 9	145 ± 1	877.5 ± 7.3	0.0751 ± 0.0007	4435 ± 45	**4249 ± 75**	888 ± 7
WY12-65	242 ± 0.9	574 ± 8	533 ± 8	882.5 ± 7.4	0.0767 ± 0.0005	4524 ± 38	**4425 ± 41**	894 ± 7
WY12-68.5	226 ± 0.6	1714 ± 35	177 ± 4	891.0 ± 4.1	0.0814 ± 0.0010	4784 ± 59	**4607 ± 101**	903 ± 4
WY12-69.5	220 ± 0.5	2009 ± 41	160 ± 4	884.7 ± 3.4	0.0882 ± 0.0010	5207 ± 60	**5007 ± 116**	897 ± 3
WY12-84	222 ± 0.5	1440 ± 29	226 ± 5	852.5 ± 3.7	0.0891 ± 0.0010	5356 ± 64	**5194 ± 96**	865 ± 4
WY12-99	215 ± 0.4	3169 ± 64	105 ± 2	848.9 ± 3.7	0.0938 ± 0.0005	5657 ± 35	**5367 ± 167**	862 ± 4
WY12-104.5	273 ± 0.7	917 ± 19	474 ± 11	818.3 ± 3.8	0.0967 ± 0.0009	5933 ± 61	**5819 ± 71**	832 ± 4
WY56-3	558 ± 0.8	5967 ± 120	56 ± 1	3082.5 ± 4.2	0.0363 ± 0.0004	973 ± 10	**831 ± 55**	3090 ± 4
WY56-36	624 ± 1.2	3946 ± 79	121 ± 3	3105.1 ± 4.7	0.0464 ± 0.0003	1237 ± 8	**1127 ± 33**	3116 ± 5
WY56-89	985 ± 2.3	3073 ± 62	303 ± 6	3114.1 ± 5.4	0.0574 ± 0.0002	1529 ± 6	**1441 ± 17**	3127 ± 5

*$\delta^{234}U = ([^{234}U/^{238}U]_{activity} - 1) \times 1000$. **$\delta^{234}U_{initial}$ was calculated based on ^{230}Th age (T), i.e., $\delta^{234}U_{initial} = \delta^{234}U_{measured} \times e^{\lambda 234 \times T}$. ***BP stands for "Before Present" where the "Present" is defined as the year 1950 CE.
The bold values highlight the corrected ^{230}Th age.

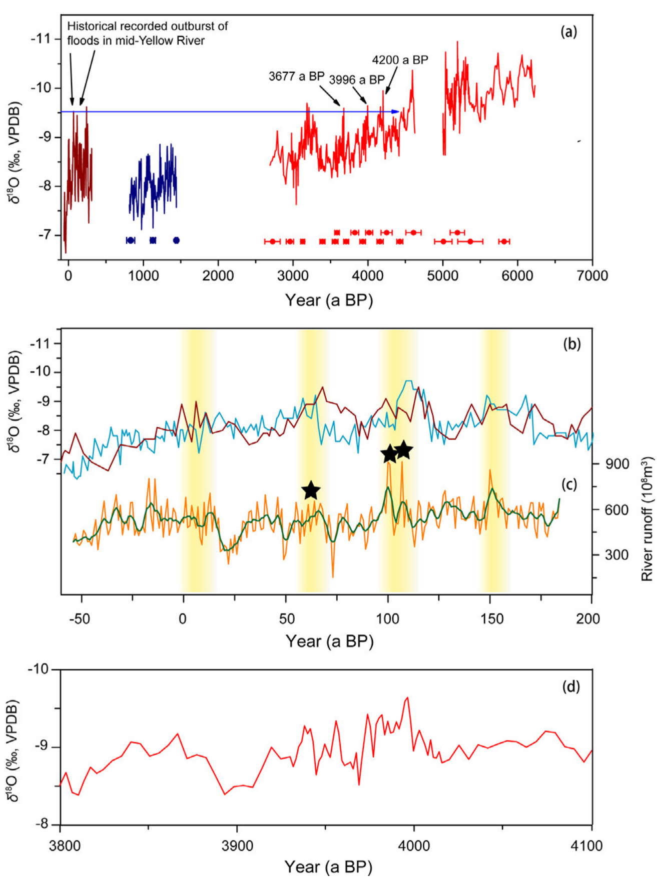

Fig. 1. (a) Stalagmite δ^{18}O inferred monsoon rainfall variations on the Loess Plateau over the past 6230 years. Brown, blue, and red lines represent WY27, WY56 and WY12 records, respectively. Three extreme rainfall events at ~4200, ~3996, ~3677 a BP, with their δ^{18}O values exceeding those when the megafloods occurred during the last 200 years, were determined. Blue and red dots indicate ^{230}Th dates with errors of WY56 and WY12, respectively. (b) Comparison between stalagmite δ^{18}O records from Wuya Cave (brown line-WY27, light blue line-WY33). (c) The observed runoff record of the middle Yellow River [8]. The green line in panel (c) is the 5-year smoothing result. Black stars denote three severe outburst floods of the middle-lower Yellow River over the past 200 years, which occurred in 1841–1843, 1855, and 1887 CE [9]. (d) Enlarged figure of the stalagmite δ^{18}O record during 3800–4100 a BP.

It was recorded that the society of the middle-lower Yellow River reaches, where ancient Xia people lived [16], did not recover even after ten years of the outburst of the flood in 1841–1843 [9]. The technology and productivity growth were much more primitive 4000 years ago than those in the 19th century. The Great Flood must have caused catastrophic damage to the ancient Xia people and have been kept in the collective memories of the society for generations. Our record indicates that the pluvial period lasted for about two decades, and then the rainfall gradually decreased (Fig. 1d). Considering the technology level in 4000 a BP, the Great Yu's control on flood might largely be ascribed to climate change [2].

With accurate ^{230}Th dating, our stalagmites reveal an extreme rainfall event on the LP around 4000 a BP, rather than an earthquake-induced landslide dam outburst flood on the eastern Tibetan Plateau at 3870 a BP [1], which probably induced the Great Flood in the middle-lower Yellow River reaches. This stalagmite-inferred age agrees well with the beginning of the Xia Dynasty estimated by previous historians and archaeologists [15], which supports the historicity of the Great Flood and the Xia Dynasty.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.scib.2018.01.023.

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