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Extraordinary flood events and the response to monsoonal climatic change during the last 3000 years along the middle Yangtze River valley, China

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ABSTRACT

Well-dated long-term flood data series is very important in studying of hydrological response to past climatic change along the mainstream of the Yangtze River. Five palaeoflood events recorded by slackwater deposits were identified by the sedimentological criteria and analytical results. A detailed chronological framework of palaeoflood events during the late Holocene was established by optically stimulated luminescence dating in combination with anthropogenic remains, and with pedo-stratigraphic correlations with well dated Holocene loess-soil profiles within the middle Yangtze River basin. The five palaeoflood events were dated to 2.43 ± 0.18 ka, 1.82 ± 0.17 ka, 0.94 ± 0.07 ka, 0.72 ± 0.06 ka and 0.59 ± 0.05 ka, respectively. These results are consistent with geological records at other palaeoflood sites and historical flood records along the middle Yangtze River valley. A regional synthesis of the palaeoflood chronology over the last 3000 years was compiled along the middle Yangtze River. Extraordinary flood events generally seem to be correlated with late Holocene climatic variability (i.e. Neoglacial cooling, Roman Warm Period, Dark Ages Cold Period, Medieval Climate Anomaly, and Little Ice Age). The high-resolution climatic proxies from stalagmites of the Dongge cave and Heshang cave, ice-cores of the GRIP, the total solar irradiance variations and sunspot number, and *ENSO* activities suggest that these hydroclimatic events are possibly related to the weaker Asia summer monsoon and the cooling climatic events, as well as the stronger *ENSO* activities during the late Holocene in the Yangtze River valley. These results provide insights into the response of hydroclimatic system to global change in the large rivers of Asia.

1. Introduction

Palaeoflood events provide a framework for more reliable interpretation of short-term instrument records, which are important archives of information in understanding extreme hydrologic event response to global climatic change (Knox and Kundzewicz, 1997; Knox, 2000). Sedimentological records of hydrological extremes can be complemented with historical documentary information and botanical records (Benito et al., 2015a, 2015b). A long-term perspective on hydrographical change was recorded by slackwater deposits (SWDs). These SWDs are typically fine-grained sand and silt that accumulate rapidly from suspension during major floods in the slackwater (back water) areas where current velocity is reduced (Baker et al., 1983; Ely and Baker, 1985; Benito et al., 2003). A series of sedimentological criteria can be used for identifying palaeoflood SWD in the field (Baker and Kochel, 1988; Benito and Thorndycraft, 2005). In our previous studies, extraordinary flood SWDs were interbedded in the Holocene loess-soil profiles at many sites along the middle reaches of the Yellow River and its tributary rivers (Huang et al., 2007, 2010, 2011, 2012a, 2012b).

Palaeoflood investigations had been carried out on the Three Gorges reach and the Jianghan Basin along the Yangtze River since the 1990s (Zhan and Xie, 1997, 2001; Yang and Xie, 1997; Zhu et al., 1997, 2005, 2008; Yang and Wang, 1997; Ge et al., 2004; Ge Z.S., 2009). The chronology of these palaeoflood events were revealed by radiocarbon that dating on wood, charcoal, buried soil and fine-organic detritus preserved in flood sediments in the lower Yangtze River (e.g., Yu et al., 2003). However, obtaining age control has been difficult due to incorporation of old organic matter into the sedimentation cycle in many fluvial sediments, which limits the application of ^{14}C dating (Rittenour, 2008; Fuchs et al., 2010). Over the last decade, optically stimulated luminescence (OSL) technology has been directly used for dating Holocene fluvial deposits, including floodplain deposits, palaeochannels, and palaeoflood sediments (e.g., Olley et al., 1998; Stokes et al., 2001; Zhang et al., 2003; Rodnight et al., 2006; Williams et al., 2010; Medialdea et al., 2014). Geochronological control for extraordinary floods and their

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palaeoclimatic implications have been established by OSL dating in the world's great river systems (Kale et al., 2000; Macklin and Lewin, 2003; Thomas et al., 2007; Benito et al., 2011; Wasson et al., 2013; Grodek et al., 2013; Greenbaum et al., 2006, 2014a, 2014b).

Palaeoflood studies have suggested that extreme floods are sensitive indicators of climate-related changes in large river systems worldwide (e.g., Ely et al., 1993; Ely, 1997; Thorndycraft and Benito, 2006; Baker, 2008; Jones et al., 2010). East Asia, with a quarter of the world's population, suffers from recurrent floods and droughts and is highly vulnerable to extreme climate change (Lim and Fujiki, 2011). The Yangtze River, the longest river in Asia, is an area sensitive to monsoon climatic change. Chronology of extraordinary flood events in the Yangtze River is too short to adequately understand the extreme hydrological event response to monsoon climatic change. To our knowledge, palaeoclimatic analysis on extraordinary flood events during late Holocene are still lacking in the mainstream of the Yangtze River valley. This paper presents our new palaeoflood investigations in the middle Yangtze River valley. These identified palaeoflood events will provide insight into the regional response of the hydro-climatic system to global change in the largest river of Asia.

2. Geographical setting

The Yangtze River valley is formed in response to regional extension throughout eastern China, synchronous with the start of strike-slip tectonism and surface uplift in eastern Tibet (Wang et al., 2013; Zheng et al., 2013). The study area is located at the margin of the loess distribution in China (Liu, 1988; Fig. 1A). Aeolian sediments (e.g., Wushan loess) have previously been identified in the middle reaches of the Yangtze River valley (e.g., Zhu et al., 1997; Jia et al., 2012; Hu et al., 2013; Wu et al., 2014). Typical loess is distributed in the north of the study area (Loess Plateau). The southern the study area is red clay, which is mainly located in the lower and middle reaches of the Yangtze River in subtropical China (e.g., Hu et al., 2010). The Xiashu loess is distributed in the eastern study area, which is mainly located in the lower reaches of the Yangtze River (e.g., Hao et al., 2010). The Ganzi loess is distributed in the western study area, which is mainly located at the west of Sichuan Province (e.g., Yang et al., 2010).

The mainstream of the Yangtze River is about 6300 km in length with a drainage area of 1.80 million km^2. It is the longest river in Asia and the third one in the world in terms of the length and discharge (Chen et al., 2001a, 2001b; Yu et al., 2009; Fig. 1B). The Yangtze River crosses the three major morphological steps from the Tibet plateau to the eastern coast (e.g. Yu et al., 2009; Fig. 1B). The upper reaches of the Yangtze River primarily run across mountainous terrain from the source to Yichang. The middle reaches of the Yangtze River lie between Yichang and Hukou. Three Gorges Dam (TGD) and Gezhouba (GZB) Dam are located at the boundary between middle and lower reaches of the Yangtze River (Chen et al., 2001a, 2001b; Fig. 1B). In the Three Gorges reach, the estimation of the largest palaeoflood, historical flood and gauging flood at the Yichang hydrological station were 114,000, 105,000 and 70,800 m^3 s^{-1}, respectively (Zhan and Xie, 2001; Ge, 2009).

Palaeoflood investigations were carried out along the upper and middle reaches of the Yangtze River during 2010–2013. The study area crosses two basins from Sichuan Basin to Jianghan Basin, which is situated in the humid zone with a subtropical monsoonal environment in China (Fig. 1B and C). The mean annual temperature is 16.9 °C and the mean annual precipitation 1200–1600 mm, which is brought about by the southeastern and southwestern maritime monsoons. The regional precipitation and hydrology are characterized by high seasonal variability with 70%–80% of rainfall occurring from June to October. Wujiang River, Jialingjiang River and the Three Gorges reach of the Yangtze River are one of important flood sources in the middle reach of the Yangtze River (Fig. 1C).

3. Sampling site and methods

3.1. Sampling site

Detailed geomorphological, sedimentological and stratigraphic observations were carried out at the WBC site. The study site lies in the translation zone between Wushan Mountains and Jianghan Basin. The five river terraces, respectively, are 10–14 m, 20–27 m, 35–42 m, 55–75 m and 95–105 m above the present river level in the Yichang reach of the Yangtze River. The first terrace is an alluvial terrace and the other terraces are bedrock terraces (Gu et al., 1983). The Holocene loess-soil stratigraphy was surveyed in detail adjacent the Weibicun (WBC) village of Yidu city, Hubei province (Fig. 1D). Two large dams (TGD and GZB Dam) are located upstream of the study site (Fig. 1C). The WBC site is located on the first alluvial terrace. The front of the WBC profile is about 10 m above the normal water level (~41 m) of the Yangtze River (Fig. 2). The Chadian station is located upstream ~3 km of the study site. The warning water level and safety water level at the Chadian station are 51.5 m and 53.3 m, respectively. The largest gauged flood, with a discharge of 53,000 m^3 s^{-1}, was recorded on August 17th 1998. The most recent large flood occurred on July 20th, 2010 with a discharge of 41,400 m^3 s^{-1} at Chadian station (Fig. 2). The elevations of top surfaces of palaeoflood SWDs only provide a minimum estimation of palaeoflood stages (Jarrett and England, 2002; Fig. 2). Because the studied reach is an alluvial reach, the estimation of palaeoflood discharge is not recommended (Baker and Kochel, 1988). These SWDs were deposited by palaeofloods with a minimum magnitude close to the largest gauged floods of 1998 and 2010 (53,000 and 41,400 m^3 s^{-1}) and seen between 48.65 and 53.29 m asl in the riverbank. The riverbanks between 48 and 51 m asl represent a threshold level for registration of extraordinary overbank floods. In the studied WBC profile at an elevation of 51 m asl on the right riverbank, several SWD bedsets were found within the Holocene loess-soil stratigraphy (Fig. 2). Thus, these SWDs were defined as the sedimentary record of extraordinary overbank flood events that occurred during the Holocene.

3.2. Methods

Pedo-stratigraphic subdivisions were observed during the fieldwork by close examination of the color, texture and structure in the WBC profile (Munsell Color Company, 2000; Schoeneberger et al., 2002). The Holocene loess-soil profiles with five palaeoflood SWDs interbeds were identified by sedimentological criteria used extensively in the world of palaeohydrology (Baker et al., 1983; Baker and Kochel, 1988; Benito et al., 2003; Benito and Thorndycraft, 2005; Huang et al., 2007, 2010, 2011, 2012a, 2012b). Detailed pedo-stratigraphic subdivisions and descriptions of the sediments in the WBC profile were shown in Table 1. Sediment samples (including 5 palaeoflood SWDs and 6 loess-soil samples) were systemically taken in the WBC profile. In addition, the 2010 and 2012 flood SWDs were collected at the WBC site for comparison with palaeoflood SWD in the same reaches (Fig. 1D). Ten OSL samples (including 4 palaeoflood SWDs, 5 loess-soil samples and 1 pottery sample) were taken at the WBC site.

OSL laboratory preparation included treatment with HCl (10%) and H_2O_2 (30%) to remove carbonates and organics matter, and dry sieving to isolate grains of 63–90 μm in size. The 63–90 μm grain fractions was

Fig. 1. (A) Map showing the distribution of loess deposits (modified from Liu, 1988) and location of study site. (B) Map showing Yangtze River drainage basin and location of major hydrological gauging stations. (C) Dem map showing topographic features of the study site (■) and other mentioned palaeoflood sites (○) along the middle reaches of the Yangtze River valley. Box outlines the study area. (D) Detailed geomorolophic map of the Weibicun (WBC) site and the location of sampling site of modern flood deposits and Chadian station in the middle Yangtze River valley.