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Late Pliocene establishment of exorheic drainage in the northeastern Tibetan Plateau as evidenced by the Wuquan Formation in the Lanzhou Basin

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ABSTRACT

The fluvial archives in the upper-reach Yellow River basins provide important information about drainage history of the northeastern Tibetan Plateau (TP) associated with geomorphologic evolution and climate change. However, the Pliocene fluvial strata within this region have not been studied in detail, hence limiting the understanding of the late Cenozoic development of regional fluvial systems. In this paper, we present the results of a study of the geochronology, sedimentology, and provenance of the fluvial sequence of the Wuquan Formation in the Lanzhou Basin in the northeastern TP. Magnetostratigraphic and cosmogenic nuclide burial ages indicate that the Wuquan Formation was deposited during 3.6–2.2 Ma. Furthermore, sedimentary facies, gravel composition, paleocurrent data, and detrital zircon U—Pb age spectra reveal that the fluvial sequence resembles the terraces of the Yellow River in terms of source area, flow direction, and depositional environment. Our results indicate that a paleo-drainage system flowing out of the northeastern TP was established by ca. 3.6 Ma and that the upstream parts of the Yellow River must have developed subsequently from this paleo-drainage system. The late Pliocene drainage system fits well with the dramatic uplift of the northeastern TP, an intensified Asian summer monsoon, and global increase in erosion rates, which may reflect interactions between geomorphic evolution, tectonic deformation, and climate change.

1. Introduction

Cenozoic uplift of the Tibetan Plateau (TP) has been thought to have significantly influenced regional erosion and global climate change, which might also have affected topographic evolution of the TP (Molnar and England, 1990; Raymo and Ruddiman, 1992; Zhang et al., 2001; Whipple, 2009). In response to the initiation of uplift, the fluvial system would have been subjected to reorganization and thus provides a critical record of topographic evolution associated with past tectonics and/or climate change (Clark et al., 2004; Clift and Blusztajn, 2005; Zheng et al., 2013; Wang et al., 2014; Nie et al., 2015).

Originated from the northeastern TP, the Yellow River is the second largest river in China (Fig. 1) and has an important impact on regional landscape development and sediment transportation. The Yellow River is deeply incised into a series of intermontane basins and tectonic ranges in its upper and middle reaches, forming multistage terraces. Based on the chronological framework of these terraces, the Yellow River is indicated to have been formed since the middle Pleistocene or later (~0.1 Ma) as a result of tectonic uplift of the northeastern TP (Li et al., 1996, 1997; Pan et al., 1996, 2009; Harkins et al., 2007; Hu et al., 2016, 2017; B.F. Li et al., 2017) or by the effect of climate change (Craddock et al., 2010; Perrineau et al., 2011; Kong et al., 2014). However, different lines of sedimentary and tectonic evidence have demonstrated that the major uplift of the northeastern TP and significant climate change commenced in the late Miocene and was intensified in the late Pliocene (Meyer et al., 1998; An et al., 2001; Zachos et al., 2001; Zhang et al., 2009; Fu et al., 2013; Craddock et al., 2014; Lease, 2014; Li et al., 2014; J.J. Li et al., 2017; Nie et al., 2017), which is substantially earlier than the uppermost terraces of the Yellow River. How regional topography evolved in response to late Miocene-Pliocene mountain building and climate change, followed by the formation of the Yellow River, are issues that remain poorly understood, mainly because of the absence of study of paleo-drainage in the northeastern TP.

The Lanzhou Basin situated on the margin of the northeastern TP and connecting upland areas upstream with lowlands downstream (Fig. 1)

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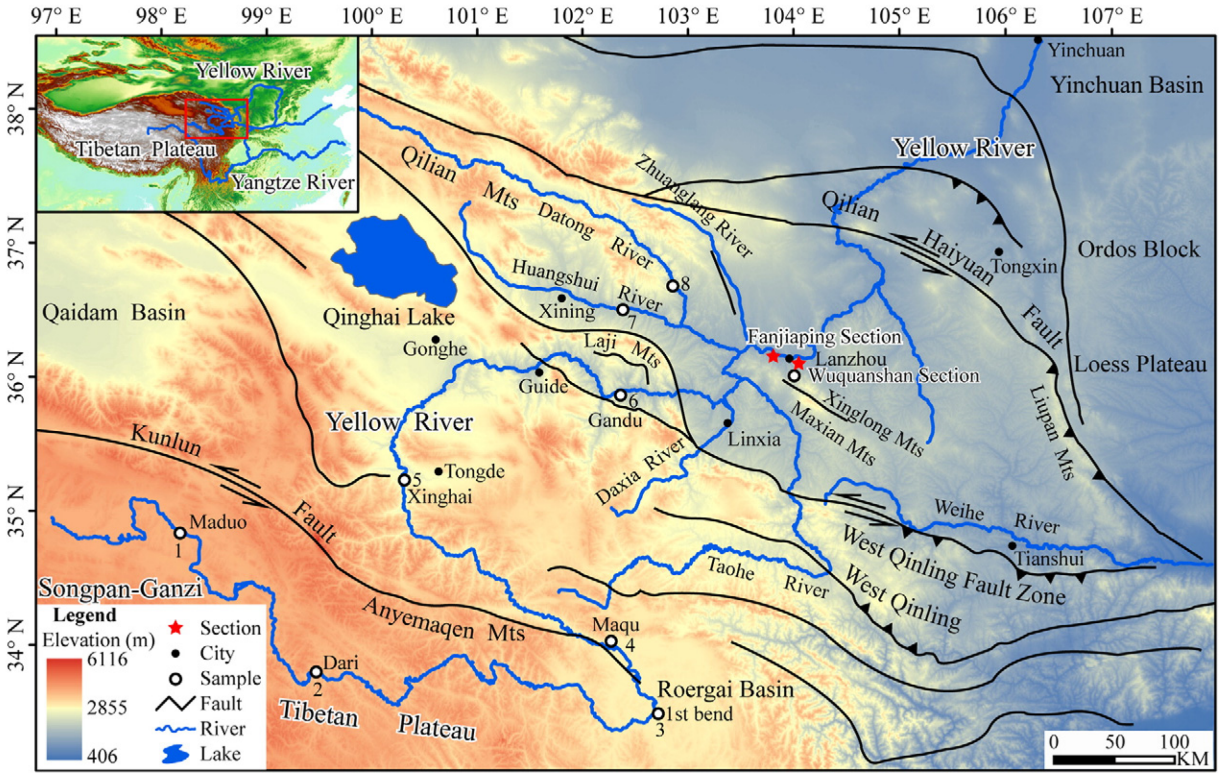

Fig. 1. Geographic setting of the Fanjiaping and Wuquanshan sections. DEM maps show the location of the Lanzhou Basin and surrounding mountains and their major tectonic and geomorphologic features. Inset map shows the location of the study area in north China. ArcGIS10.2 was used to create the base map. The SRTMDEMUTM 90-m data were obtained from http://www.gscloud.cn/.

is well-suited to testing whether paleo-rivers ran through the plateau margin. Specifically, the Lanzhou Basin contains a unique Pliocene to early Pleistocene fluvial archive in the form of the Wuquan Formation (Gu and Zhang, 1987; Wu et al., 1988), although its precise age, lithology, and provenance have not been studied in detail. This paper presents new data on paleomagnetic chronology, cosmogenic nuclide burial ages, detrital zircon U—Pb ages, and conglomerate analyses to illuminate the nature of the Wuquan Formation, as well as its implications for understanding long-term drainage history and geomorphic evolution of the northeastern TP, coupled with tectonic deformation and climate change.

2. Regional geological and geomorphic setting

The northeastern TP is tectonically bounded by the sinistral strike-slip Kunlun Fault to the south and the Qilian-Haiyuan faults to the north (Fig. 1). It consists of a series of NWW-trending high tectonic ranges (ca. 4000–5000 m in elevation), e.g., the Anyemaqen Mountains, the Eastern Kunlun Mountains, the West Qinling Mountains, and the Qilian Mountains. These ranges confine many sedimentary basins that contain hundreds to thousands of meters thickness of Cenozoic terrigenous sediments (Lease, 2014; Li et al., 2014; Fig. 1). The northeastern TP lies at the junction of the areas impacted by the East Asian monsoon, the northern arid climate, and the climate of the Tibetan highlands (Li et al., 2014; Zhang et al., 2016). In northeastern TP, the modern Yellow River flows from the Anyemaqen Mountains at ~3300 m elevation, descends through a series of basins and ranges, enters the Lanzhou Basin at ~1500 m elevation, and then turns northeastward at ~1000 m elevation (Fig. 1).

The late Cenozoic Lanzhou Basin is extruded east-west and stretched from south to north, being regulated by the Maxian-Xinglong Fault to the south and the Zhuanglang Fault to the west (Yuan, 2007; Yuan et al., 2008; Figs. 1 and 2). It belongs to the Qilian orogenic belt. The bounding ranges of the basin are the Qilian Mountains, the Maxian-Xinglong Mountains, and the Laji Mountains (Fig. 1), which consist largely of Precambrian and lower Paleozoic metamorphic rocks, early Paleozoic plutons, and Lower Cretaceous sedimentary rocks (Zhai and Cai, 1984; Gehrels et al., 2003; Tung et al., 2016). The geological setting contrasts significantly with the plateau ranges of the West Qinling and Songpan-Ganzi terranes, which are mainly composed of Triassic submarine fan deposits and Permo-Triassic plutons (Weislogel et al., 2010). Moreover, the Lanzhou Basin is filled with massive alluvial-lacustrine red strata dominated by successive mudstones, limestones, and gypsum intercalated with limited braided river and fan-delta sandstone layers with a total thickness of 1000–2000 m. The red strata are of Eocene to late Miocene age, based on magnetostratigraphy constrained by biostratigraphy (Yue et al., 2000; Y.P. Zhang et al., 2014; Ao et al., 2016; Wang et al., 2016). Following the termination of basin infilling, the Wuquan Formation and pediment surface were formed in the late Pliocene or early Quaternary (Gu and Zhang, 1987; J.J. Li et al., 2017). The Yellow River continued to cut downward and to develop a series of terraces (Li et al., 1996, 1997). This sedimentary sequence is overlain by a Quaternary loess-paleosol sequence with a typical thickness of 400 m (Burbank and Li, 1985; Li et al., 1999; Zhang et al., 2016).

The Wuquan conglomerate, originally named as the Wuquanshan System by Young and Bien (1937), unconformably overlies the Eocene-Miocene red beds. The two main outcrops within the Lanzhou Basin are the Fanjiaping and Wuquanshan sections. The Fanjiaping section (36°04′55.9″ N, 103°40′07.8″ E; Figs. 1 and 2) is on the southern bank of the Yellow River, in the depocenter of the Qilihe depression zones, which are dominated by the Leitanhe, Shengouqiao, Xijincun, and Jinchengguan faults. The Wuquanshan section (36°01′50″ N, 103°49′48″ E; Figs. 1 and 2), which lies on the hanging wall of the Leitanhe thrust fault (Yuan et al., 2008), is composed mainly