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Alluvial fan aggradation/incision history of the eastern Tibetan plateau margin and implications for debris flow/debris-charged flood hazard

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ABSTRACT

This paper reconstructs the Quaternary aggradation and incision history of a debris flow/debris-charged flood-affected valley in order to detect the impact of climate on alluvial fan dynamics. We used optically stimulated luminescence (OSL) dating of quartz to determine the ages of alluvial fan terraces. Comparison between the aggradation and incision history and regional climatic records suggests that aggradation occurred in cold and/or dry climates, whereas incision is a feature of warm and wet climates. Cold climates lead to enhanced frost shattering, and dry climates cause deteriorated vegetation. Both effects caused surplus sediment, which was transported by infrequent flood discharges to form alluvial fan/terrace deposits. Incision during wet and warm climates is due to increased vegetation cover and an increase in the frequency of flood discharges. This relationship between climate and valley evolution is applied to assess future changes in the present active channel by considering recent climatic records. The results show that the valley channel is expected to experience net incision if the average temperature continues increasing while precipitation maintains at a constant level.

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1. Introduction

The eastern margin of the Tibetan Plateau is characterized by large rivers incising into the uplifted topography resulting from the continued convergence between the Indian and Eurasian plates (Clark and Royden, 2000; Kirby et al., 2002; Ouimet et al., 2007). Alluvial sediments, which are sourced from tributary valleys, are deposited on the valley floors of these large rivers, forming tributary-junction alluvial fans (Harvey, 1997, 2011; Al-Farraj and Harvey, 2000, 2005; Stokes and Mather, 2015). These types of alluvial fans have smaller extensional areas than those developed in mountain-front settings (Sohn et al., 2007; Spelz et al., 2008; Kar et al., 2014; Harvey et al., 2016), whilst they usually develop multiple fan levels representing alternations between aggradation and incision (Harvey and Renwick, 1987; Al-Farraj and Harvey, 2000; Harvey, 2002; Juyal et al., 2010).

Knowledge of the factors causing changes of regime between aggradation and incision has been a key question in alluvial fan research (Harvey, 2012; Owen et al., 2014). Understanding the regime is crucial in regulating fan-building processes such as debris flows or floods for hazard mitigation (Jakob, 2005; Welsh and Davies, 2011; Santangelo et al., 2012). This need is particularly urgent in the eastern margin of the Tibetan Plateau, where a proportion of the population lives on the alluvial fans (Tang et al., 2011; Zhang et al., 2011; Xiong et al., 2016). Among the factors that influence fan development (e.g., tectonism, climate and base level), climate has been regarded as a dominant factor in millennial timescales across the world (Ritter et al., 1995; McDonald et al., 2003; Pope and Wilkinson, 2005; Suresh et al., 2007; Kar et al., 2014; Owen et al., 2014). This paper aims to understand the relationship between fan dynamics and climate in a tributary valley of the Bailong River, which is one of the main rivers connecting the Tibetan Plateau and the Sichuan Basin.

Detailed mapping and borehole drilling highlight four stages of aggradation/incision during the evolution of alluvial fans in the valley. Here, we produce a chronology for the aggradation and incision periods using optically stimulated luminescence (OSL) dating of quartz derived from terrace and borehole sediments. The aggradation and incision periods are then compared with well-dated regional climatic records to examine how alluvial processes respond to climatic changes. Finally, the past relationships between climate and valley evolution are used to infer future debris flow/debris-charged flood hazards in the valley, representing a new approach to understanding long-term debris flow/debris-charged flood hazards.

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2. Research contexts

2.1. Study area

The Bailong River is a primary tributary of the Yangtze River. It originates on the Tibetan Plateau at an elevation of ~6000 m and flows southeast through three counties, Zhouqu, Wudu and Wen, of Gansu Province (Fig. 1). The middle section of the Bailong River (i.e., between Zhouqu and Wudu) (Fig. 1), is an area with locally high population density. The county centers of Zhouqu and Wudu, and various other town centers, are situated on the alluvial fans or fluvial terraces of this section of the river. Geologically, this section of the river has developed in an anticline system (Li, 1994) that folded the region between the Silurian and Permian. The anticline hinge was eroded, forming relatively low-relief, low-elevation hillslopes and river valleys (Zhang et al., 2011), while the anticline limbs formed high-relief, high-elevation hillslopes that became the headwaters of tributary valleys feeding the Bailong River.

The Goulinping (GLP) River (N 33°32′24″, E 104° 39′13″), with a watershed area of ~20 km^2 and a relief of 1897 m, is located in the middle section of the Bailong River (Fig. 2). It is sourced from a high-relief limestone area and subsequently passes through a low-relief phyllite area before finally entering the Bailong River (Fig. 3). To demonstrate the representativeness of the GLP River in the middle section of the Bailong River, three key geomorphic parameters, drainage area (A), hypsometric integrals (HI) and relief of the tributary valleys were calculated using the spatial analyst tools in ArcGIS 10.2 (Fig. 2). Tributary valleys in the middle section of the Bailong can be grouped into three categories based on their drainage areas: small-sized valleys ($A < 10$ km^2), intermediate-sized valleys ($10 \le A \le 100$ km^2) and large-sized valleys ($A > 100$ km^2) (Fig. 2b). Fig. 2 demonstrates that the intermediate-sized tributary valleys account for a primary proportion of the middle section of the Bailong and generally developed from relatively high-elevation (>2500 m) areas. These intermediate-sized valleys have HI values between 0.41 and 0.60 (Fig. 2c), and relief between 1645 and 2405 m (Fig. 2d). The GLP valley (intermediate-sized) has a HI value of 0.47 and a relief of 1897 m, both of which fall in the range of the HI and relief values for the intermediate-sized valleys, making it representative of many intermediate-sized tributary valleys in the middle section of the Bailong River.

Climate in the study area is controlled by the Asian monsoon system, which is characterized by warm and humid summers and dry and cold winters (Railsback et al., 2014). The area receives an annual precipitation of 487.2 mm, 75 to 85% of which falls between May and September. The average minimum and maximum temperatures are −14 °C to 3 °C in January, and 11 °C to 27 °C in July (Johnson et al., 2006).

2.2. Alluvial fan/terrace settings

Four levels of alluvial fans/terraces (denoted as F1, F2, F3 and F4 from the lowest to the highest elevation) are identified based on field investigation (Fig. 3). These sedimentary bodies are characterized by alluvial fans at the valley mouth and alluvial terraces upstream. These alluvial terraces sourced from the limestone headwaters have fed the alluvial fans at the valley mouth. The F3 and F4 alluvial fans/terraces are distributed across the phyllite valley, while the F1 and F2 alluvial fans/terraces are only present close to the phyllite valley mouth (Fig. 3).

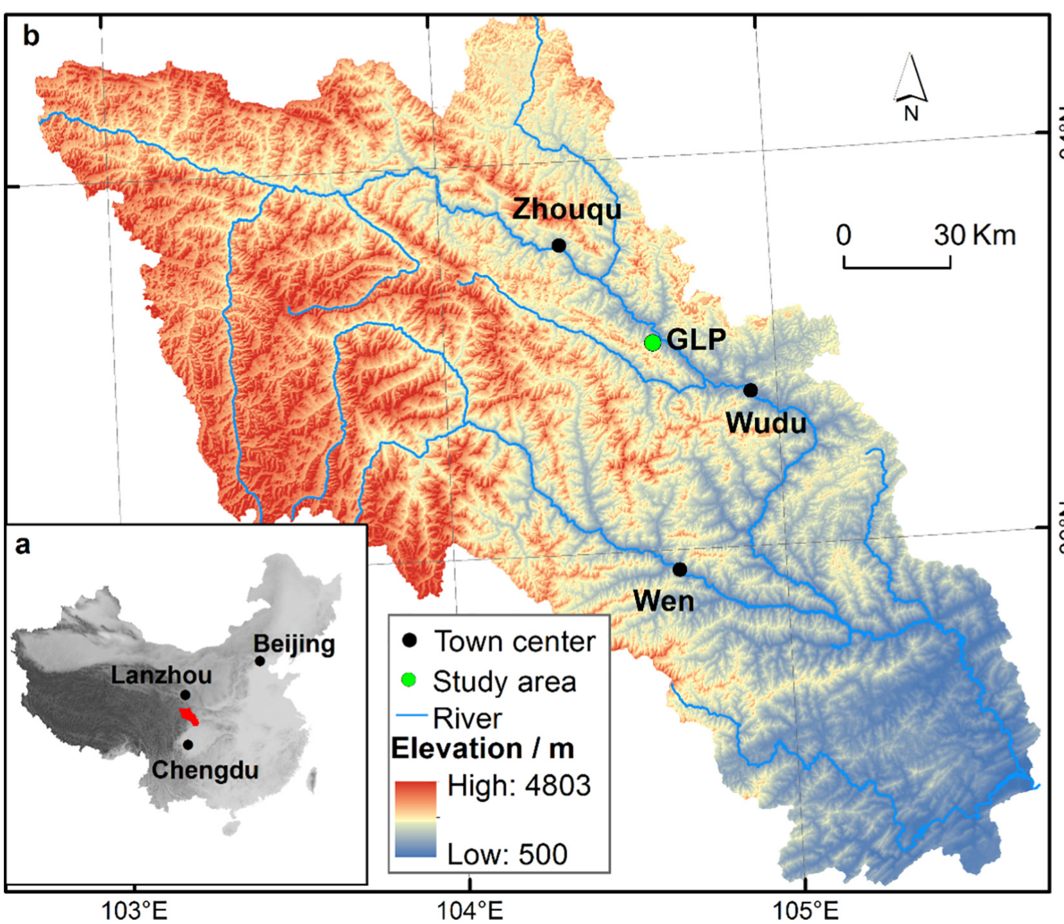

Fig. 1. Location of the Bailong River and the GLP valley. (a). Location of the watershed (the area shaded in red) within China. (b). DEM of the Bailong River watershed and the location of the GLP valley. The background image is a 30-m resolution ASTER DEM. Zhouqu, Wudu and Wen are the three important county centers along the Bailong River.

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