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Evaluating fluvial terrace riser degradation using LiDAR-derived topography: An example from the northern Tian Shan, China

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ABSTRACT

The morphological degradation of fluvial terrace risers provides a constraint to terrace chronology. In this study, we morphologically date the terrace risers along the Kuitun River on the north flank of the Tian Shan, China and subsequently discuss possible relationships between terrace formation and the past regional climate changes and tectonic activity of the Dushanzi fault-related fold. To do this, 159 topographic profile swaths of terrace risers were extracted from LiDAR-derived DEM and were analysed to determine a range of best fitting morphological ages. Through Monte Carlo simulation, a locally applicable sediment transport coefficient (diffusivity) was calibrated as 5.5 ± 1.6 m^2/ky given the morphological age of the T1/T2 riser and its independently known age. Taking this calibrated coefficient, we estimate age ranges of 11.6 ± 3.4 ka, 6.5 ± 1.4 ka, 5.3 ± 1.1 ka, and 4.2 ± 1.2 ka for terraces T3, T4, T5, and T6, respectively, under the assumption that the age of the riser is close to the abandonment age of the lower surface. These new terrace ages, combining climate proxy records from the oxygen isotope curve from the Guliya ice cap and paleoearthquake events in the Dushanzi fault related fold, suggest that tectonic activity may be an important factor in the formation of lower terraces within the growing anticlines, while in more extensive areas beyond anticlines, climate changes controlled the main deposition and incision events in the present study area, and thus terrace formation of T1–T3.

1. Introduction

River terraces are an important geomorphological component of fluvial systems in many arid and semiarid regions, such as northwestern China. River terrace sequences are the combined result of Quaternary tectonic uplift and climatic change (Molnar et al., 1994; Deng et al., 1996; Starkel, 2003; Bridgland and Westaway, 2008; Wang et al., 2009). Accurate dating of these terraces is essential to evaluate the relative roles of tectonism and climate in Quaternary terrace evolution (Ritter et al., 1995; Maddy et al., 2000) and to constrain the kinematics of active faults when fluvial terraces are used as makers of fault offset (Cowgill, 2007; Kirby et al., 2007; Zhang et al., 2007). In arid and semiarid regions, however, organic material is rare, which makes ^{14}C dating a challenging endeavour. Despite the great power of radiometric methods such as cosmogenic nuclides (e.g., Molnar et al., 1994; Gosse and Phillips, 2001; Schaller et al., 2001), they are costly and time intensive. Morphological dating based on profile change as a consequence of slope-dependent sediment transport may provide estimates of the age of scarps developed in unconsolidated alluvial material (assuming the transport rate is independently known; Culling, 1960; Nash, 1980; Hanks and Wallace, 1985; Avouac and Peltzer, 1993; Hsu and Pelletier, 2004). By assuming that mass transport is proportional to the local topographic slope and that mass is locally conserved, the age of the scarp can be estimated by using the diffusion equation to model the topographic evolution of the scarp as it degrades (e.g., Arrowsmith et al., 1998; Hanks, 2000). Thus, erosional degradation of the terrace riser (the steep slope that separates adjacent terrace treads) can potentially provide a direct constrain on the terrace chronology because the riser was last eroded (refreshed) by the channel (Pierce and Colman, 1986; Avouac and Peltzer, 1993; Cowgill, 2007; Harkins and Kirby, 2008).

Morphological dating requires high-resolution cross-scarp topographic profiles. Most previous studies of scarp degradation were based on labour-intensive ground surveying, so a small quantity of topographic profiles was selected for each location (Hanks and Wallace, 1985; Nash, 1980). There is potential risk to determining the correct diffusive age of scarp by a small amount of profiles due to diachroneity of riser age (Harkins and Kirby, 2008).

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Quantitative estimates of fluvial scarp ages began to be inferred from their topographic form using field survey profiles in areas where mass transport rates could be calibrated with absolute age dating methods under the assumption of diffusive transport (e.g., Pelletier et al., 2006; Harkins and Kirby, 2008). This type of morphological dating and analysis is highly dependent on transect selections, orientation and profile line. These transect selections have been performed through the qualitative assessment of the geomorphologist in the field (Hylland, 2007; Clarke and Burbank, 2010). High-resolution Digital Elevation Models (DEMs) from LiDAR (Light Distance and Ranging) can significantly improve the representation of land surfaces (e.g., Carter et al., 2007). Due to their fine representation of the topography (~1 m or finer) and their digital format, numerous topographic profiles can be extracted from LiDAR-derived DEM and analysed for morphological age without the need for laborious field survey transects (Crosby et al., 2004). A statistical analysis of morphological ages from numerous profiles can then constrain the relative ages of landforms in a research area. Once calibrated, landforms (for example, fault scarps, shorelines and terrace risers) across the region can be quickly dated via a profile-based analysis of the LiDAR-derived DEM.

The topography of the northern piedmont of Tian Shan presents a clear record of the interaction between tectonic and channel incision processes. This interaction has resulted in the formation of characteristic landforms such as fill-cut terraces in uplifted valleys, fault scarps and fluvial terrace sequences, all of which provide an excellent field setting to test the morphological dating technique. In this study, we apply the diffusion model to the recently acquired LiDAR topography data from fluvial terraces along the Kuitun River across growing anticlines on the north flank of the Tian Shan, China. The goals of this paper are to (1) obtain the age of terrace risers using a diffusive hillslope degradation model, and then constraining the abandonment age of related terrace treads; (2) evaluate the possible contribution of climate change and tectonic activity to the terrace formation; and (3) develop a scheme for exploiting LiDAR data for landform correlation by conducting profile-based morphological dating (using linear diffusion) of fault scarps and marine, lake and fluvial shorelines.

2. Study area

2.1. Geological setting

The east–west-trending Tian Shan is a mountain range in central Asia, that separates the Tarim Basin to the south from the Junggar Basin to the north. In response to the India-Asia collision during the late Cenozoic, the Tian Shan has been tectonically reactivated and uplifted, which has resulted in the intensive deformation of the Mesozoic to Cenozoic strata in the foreland basins (Windley et al., 1990; Avouac et al., 1993; Deng et al., 2000; Zhang, 2004). The neotectonics in the north flank of the Tian Shan are characterised by the sequential forward propagation of several thrust-related folds, indicating a north–south contraction and crustal shortening (Zhang et al., 1995; Burchfiel et al., 1999). Consequently, three parallel rows of thrust-related fold (A, B and C in Fig. 1) have developed in the northern piedmont of the Tian Shan. Except for the first row closest to the Tian Shan, the other

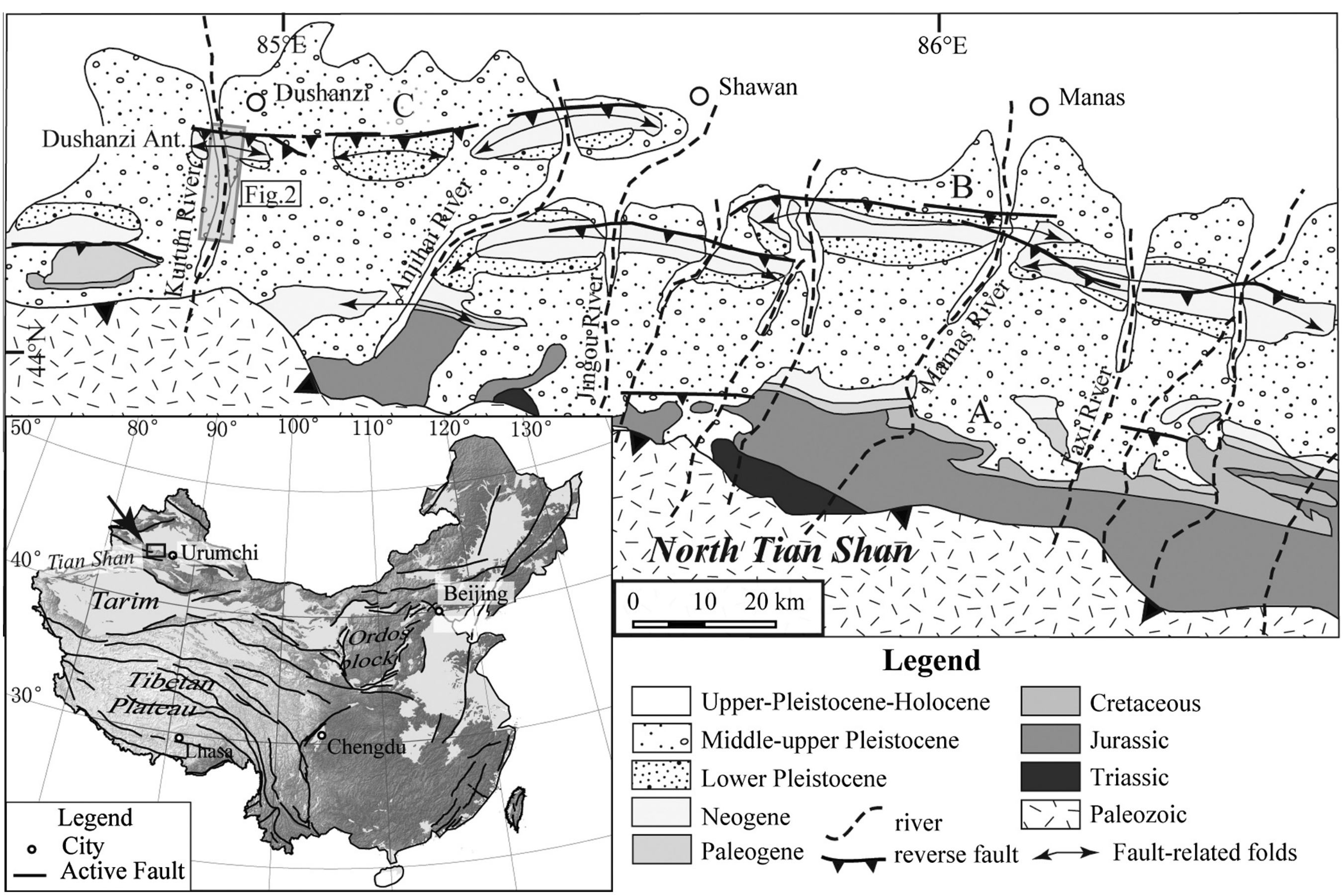

Fig. 1. Sketch map of tectonics of China and generalised geological map of the northern piedmont of the Tian Shan, northwestern China (modified from Lu et al., 2014). (a) Main active fault distribution of China (modified from Deng, 2007), black rectangle shows the location of (b); and (b) anticline-reverse fault zones along the northern piedmont of the Tian Shan and the drainage system across them, grey rectangle indicates the study area where the Kuitun River cuts through the Dushanzi Anticline-reverse fault zone.