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Late Quaternary alluvial fan terraces: Langshan, Inner Mongolia, China

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ABSTRACT

Alluvial fan terraces of the Langshan Range in the northwestern Hetao Basin of northern China records uplift on range-bounding faults and late Quaternary climate change. Alluvial fan profiles are segmented in the central part of the range front, which lack strath terraces that developed in the southwest (SW) and northeast (NE) parts. The stream channels in the central part have higher channel gradients and lower ratios of the valley floor width to valley height (*V*). Four episodes of alluvial fan terraces were upstream from the range-bounding fault, which formation ages were estimated as ~116, 64, 35, and 10 ka BP according to optically stimulated luminescence (OSL) dating combined with previous ^{14}C and OSL ages. The correlation between time of the terraces formation and climatic fluctuations recorded in a Guliya ice core reveals that alluvial fan aggradation was concentrated during the cold stages and that incision occurred during the succeeding cold-to-warm transitions. A majority of alluvial fan terraces developed in accelerated uplift since ~64 ka, which indicates that tectonic uplift provided the driving force for continuous downcutting after climatic change triggered it. Geomorphic indices (channel gradient and *V*) distribution reconstructs the model of discrepant uplift in the Langshan Range with the fastest uplift rate in the central part, which is controlled by range-bounding faults.

1. Introduction

Landform evolution is particularly sensitive to changes of tectonic activity and climate. A fluvial system is a primary agent for shaping landscape evolution controlled by climatic changes and tectonic deformations (Sinha et al., 2010). Thus, terraces have been used successfully as a tool to reconstruct past tectonic perturbations and climatic changes (Maddy et al., 2001; Starkel, 2003; Steffen et al., 2010; Stokes et al., 2012). In a dry environment, fluvial systems often lack sediment and vegetation, which makes them more sensitive to tectonic and climatic change (Prizomwala et al., 2016).

Alluvial fans provide a significant record of tectonic and climatic changes as fluvial landforms often developed in front of faulted mountain ranges in arid and semiarid regions (Sarıkaya et al., 2015; Sarp, 2015). Several studies have focused on the roles of tectonic perturbations and climatic changes in the processes of alluvial fan development (e.g., Dorn, 1996, 2009; Harvey et al., 2005; Quigley et al., 2007). Some workers have proposed that global/local climate proxies and the development of alluvial fans are closely related (Waters et al., 2010). Others claim that tectonic processes are among the major controlling mechanisms for the development of alluvial fans (Bull, 1977; Allen and Hovius, 1998; Densmore et al., 2007). An alternate view is that the formation of alluvial fans is the result of the interaction of climate change and tectonic uplift (Starkel, 2003; Bridgland et al., 2004; Maddy et al., 2008; Wang et al., 2010; Liu et al., 2011). Climate change controls the accumulation-cutting behavior of fluvial systems, whereas tectonic uplift determines the range of the incision (Maddy, 1997; Pan et al., 2003). The debate over the importance of these processes is derived from limitations such as the nonrepresentative nature of sedimentation and the mismatch between precision and accuracy of dating techniques as opposed to paleoclimatic records (Dorn, 2009).

The chronometry of alluvial fan surfaces provides important clues on the extent and intensity of tectonic activity along the active faults (Cunha et al., 2008). Topography and drainage development can also provide key information about tectonic control on landform evolution (Azor et al., 2002; Kale et al., 2014). Morphometric parameters have been widely used as a tool to identify and characterize the tectonic deformation of active faults (Pedrera et al., 2009; Pérez-Peña et al., 2010). Particularly, the morphometric properties of alluvial fans have been employed successfully (Goswami et al., 2009; Saqqa and Atallah, 2013). In this study, we present a statistical chronology and morphology for abandoned alluvial fan surfaces to better understand the interplay of fan development and regional tectonic uplift. Concurrently, we

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reconstruct the model of the regional mountain uplift based on spatial distribution of morphometric indices, channel gradient, and ratios of the valley floor width to valley height (V).

The Langshan Range is located in the northwestern margin of the Hetao Basin in northern China, which is a typical arid and semiarid subtropical area (Guo et al., 2017) and an east Asian monsoon region. Its sediments and landforms have sensitive responses to climatic fluctuations. Piedmont fault activity in the area was intensive and inhomogeneous during the late Cenozoic, resulting in continuous and discrepant mountain uplift and the sinking of the Hetao depression, which has been the focus of many studies (Sun et al., 1990; Deng et al., 2002; Cheng et al., 2006). In particular, neotectonic movements have been comprehensively studied from different aspects, such as the piedmont active faults (Sun et al., 1990; Deng et al., 2002; Research Group of Active Fault System around Ordos Massif, 1988), erosion surface (Cheng et al., 2006), piedmont Yellow River terraces (He et al., 2014), and strath terraces (Jia et al., 2015). However, quantitative studies on tectonic uplift are few in the central Langshan Range where strath terraces are nonexistent but the alluvial fan terraces well developed. A concrete model of the discrepant uplift in the Langshan Range has never been presented. Moreover, relatively unscathed alluvial fan terrace sequences are preserved in the fault-controlled piedmont zones. As discussed above, geomorphic and sedimentary features of alluvial fans that developed in arid and semiarid subtropical areas with active tectonism are more useful to reveal the roles of climatic change and tectonic activity in the development of fan terraces. Additionally, this study also gives a case study for tectonic uplift research in worldwide fault-controlled mountain ranges based on alluvial fan terraces.

This paper provides a comprehensive study of alluvial fan sediments and landforms in the central part of the Langshan Range, including their temporal and spatial distribution characteristics. We establish the chronological framework of alluvial fan terraces in the Langshan Range by averaging newly obtained OSL ages and previous ^{14}C and OSL ages of stepped landforms. The correlation between formation time of alluvial fan terraces and climatic fluctuations recorded in Guliya ice cores, Tibetan Plateau, China (Wu et al., 2004), reveals climatic change during the development of alluvial fan terraces combined with grain size analysis of sediments. We propose a relationship between terrace development and tectonic uplift by analyzing estimated incision rates. Based on the spatial distribution of morphometric indices (channel gradient and V) in the Langshan Range, we present an uplift model for the Langshan Range during the late Quaternary. This study will provide reliable evidence to solve a controversial issue in the world: how do climatic change and tectonic activity control the development of fan terraces.

2. Geological background

The Langshan Range is located in Bayannur district, Inner Mongolia, China (Fig. 1A), and is characterized by an arid and semiarid subtropical climate with sparse vegetation. The study area is located in the transition zone between the Hetao Basin and the Langshan Range in the western Yinshan orogenic belt (Fig. 1B). The Langshan Range trends between NE-SW and NEE-SWW, with a slightly northward arcuation. It is ~370 km in length and has an average altitude of 1500–2200 m. The northern slope is relatively gentle, and the southern part has a fault scarp that borders the Hetao Basin. A piedmont river system is developed near the SE-NW stretch, where 4–5 river terraces are also recognized (Jia et al., 2015) along with the NE and SW segments, with narrow seasonal drainages in the central part of the mountain (Fig. 1C).

The exposed strata in the study area are composed of Archean Wulashan Group grey-black gneisses, Mesoproterozoic Chaetai Group terrigenous clastic rocks, Middle-Lower Jurassic Shiguai Group grey-green feldspar sandstones with fine siltstones, Cretaceous Lisangou Formation grey and purple sandstones and conglomerates, and Quaternary strata. Most of these are highly weathered and severely fragmented. The Quaternary strata are composed of diluvial, alluvial, and lacustrine sediments, with a thickness of ~2400 km in the basin (Chen, 2002). The sediments on the basin surface mainly formed in late Pleistocene (Li, 2006). The Holocene alluvium distributes discontinuously over the Langshan piedmont, constituting an alluvial fan group.

The formation of the Langshan landscape is closely related to its tectonic background. The Langshan Range formed during a period of crustal thickening and deformation (Darby and Ritts, 2002, 2007). In the early Cenozoic-Eocene (E2), the effects of the Himalayan orogeny increased the NW-SE tension, resulting in crustal distention (Jia et al., 2015). The weak tectonic zone formed by the Yinshan movement generated a tensional fracture trending nearly NE-SW. It includes large-scale normal faults along the southern margin of the Langshan Range (Fig. 1B), initiating uplift of the Langshan Range (He et al., 2014; Jia et al., 2015) and sagging of the Hetao Basin. This provides thousands of meters thick accommodation space (Sun et al., 1990).

In the late Quaternary, uplift of the Langshan Range continued but was inhomogeneous (He et al., 2014; Jia et al., 2015). Since the Holocene, tectonic movement in the Langshan area has been active, accompanied by frequent seismic activity (Research Group of Active Fault System Around Ordos Massif, 1988).

3. Study methods

3.1. Sampling and pretreatment

Particle size of the alluvial sediments in the Langshan Range shows wide variation, from very large boulders to clay. Embracing all grain size samples is not applicable for granulometric analysis. We thus measured the diameters of boulders or large gravels in the field and collected fine samples (<2 mm) for laboratory analysis using the particle size analyser Mastersizer 2000. Samples were collected from 0.2 to 0.5 m below the surface in order to avoid the effect of later modification. Particle size classification is according to Wentworth classification (Wentworth, 1922): gravel grade (>2 mm); sand grade (2–0.063 mm); silt grade (0.063–0.004 mm); and clay grade (<0.004 mm). Particle size distribution has been altered owing to the mixing of organic debris and carbonate sediments with terrigenous clasts during transportation and deposition, causing imprecise analysis results. Pretreating the samples is thus necessary to recover the original grain size distribution. The following procedures are adopted for this purpose: place 0.2–0.5 g sample in a 400-ml beaker, add 10 ml 10% hydrogen peroxide (H_2O_2), then heat the mixture to 210 °C to eliminate the organic matter. At the elevated temperature, add 10 ml 30% hydrochloric acid (HCl) to the beaker to remove the carbonates. Then add 300 ml distilled water to cool down the beaker. Thereafter, change the liquid in the beaker every 24 h until its contents become neutral (pH = 7). Finally, leave the sample with 50–70 ml of water in the beaker under ultrasonic acoustic vibrations for 10 min to disperse the particles and use the particle size analyser Mastersizer 2000 to analyze the grain size distribution.

3.2. Measurement and calculation

The present study combines remote sensing techniques with geological field investigation. It focuses on the characterization of alluvial fan geomorphology and sedimentation, their spatial and temporal distribution, and the reconstruction of climatic and tectonic fluctuation. The incision rates in the Langshan Range were estimated by calculating ratios of the relative altitudes and formation ages of the alluvial fan terraces. We determined the relative altitudes of the terraces and sediment thicknesses in field measurement by GPS and Google Earth.

3.3. Geochronology

Undisturbed alluvial fan terrace deposit matrices were collected for OSL dating. Use the open end of a steel tube (6 × 25 cm) with one sealed