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DEM and GIS analysis of geomorphic indices for evaluating recent uplift of the northeastern margin of the Tibetan Plateau, China

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ABSTRACT

The northeastern margin of the Tibetan Plateau is a tectonically active region consisting of a series of faults with bounded intermountain basins and is located in the transition zone between the Tibetan Plateau and the Loess Plateau. Active deformation that may affect the topography in this region can be quantified using geomorphic indices. Therefore, we applied geomorphic indices such as the hypsometric integral and the stream length gradient index to infer neo-tectonics in the northeastern margin of the Tibetan Plateau. Different time-scaled geodetic leveling data and river incision rates were also integrated into the investigation. The results show that the hypsometric integrals are not significantly affected by lithology but spatially correspond to the hanging walls of thrust faults. The hypsometric integrals are also positively correlated with the leveling data. Although the stream length gradient index is influenced by lithology, its most pronounced anomalies of the stream length gradient are associated with the thrust faults. Consequently, the uplift in the northeast margin of the Tibetan Plateau appeared to be concentrated along the hanging walls of the thrust faults.

1. Introduction

Geomorphic indices are capable of detecting landform responses to tectonics and therefore have been broadly used to investigate tectonic geomorphology (e.g., Brookfield, 1998; Keller and Printer, 2002; Chen et al., 2003; Kobor and Roering, 2004; El Hamdouni et al., 2008), and some indices are particularly useful for identifying relative tectonic activity. Moreover, the increasing availability of digital elevation models (DEMs) and GIS software has facilitated the large-scale characterization of landscapes (e.g., Bishop et al., 2002, 2003; Korup, 2005; Troiani and Della Seta, 2008; Walcott and Summerfield, 2008; Pérez-Peña et al., 2009). Recently, the hypsometric integral (*HI*) has been applied to evaluate the developing stages of structurally controlled drainage basins in Taiwan and Iran (Chen et al., 2003; Dehbozorgi et al., 2010). The stream length gradient index (*SL*), which describes the morphology of a stream network (Hack, 1973; Keller and Printer, 2002), has also been used for the quantitative investigation of relative tectonic activities in central Italy and France (Troiani and Della Seta, 2008; Font et al., 2010). Because both indices can be used to evaluate the effects of tectonic activity on topography (Keller and Printer, 1996), we use them to evaluate relative rates of deformation in the northeastern margin of the Tibetan Plateau (NETP) (Fig. 1). This area represents a transitional zone between the Tibetan Plateau and the Loess Plateau in central China. The geomorphic work is motivated by three points: (i) Although the basic parameters of elevation, slope gradient and relief characterize large-scale deformation patterns (Liu-Zeng et al., 2008), the hypsometric and channel indices have not been applied to evaluate tectonic activity in this region; (ii) due to the widespread loess cover, the faults are difficult to trace in the field. Thus, the geomorphic indices can aid in the detection of geomorphic anomalies induced by concealed faults; and (iii) although the slip rates of several major faults have been measured, recent vertical deformation data have been sparsely documented (Table 1, Fig. 2), and the slip rates are mainly determined by dating displaced fluvial terraces, alluvial fans or strata in trenches (Li et al., 1997; Wang et al., 2010). The application of geomorphologic indices could provide semi-quantitative information on tectonic deformation rates for the entire study area.

Verification of how well the geomorphic indices reflect the actual geological setting is important, and the preserved fluvial terrace sequences may provide keys to understanding the Quaternary uplifts of the region. Thus, the combined analysis of geological, geodetic, and geomorphic data and field evidence is required. In the study area, most of the dated terraces are distributed along the main channel, which may not reflect the active tectonics of the entire region. Therefore, evaluating active tectonics on a regional scale is a difficult task. However, geodetic data supply information on present-day crustal movements, and a large-scale geodetic study for China has been carried out by Hongwen et al. (2002). Their results suggest uplift rates of up to 4 mm yr^{-1} in the northeast margin of the Tibetan Plateau, although the integration

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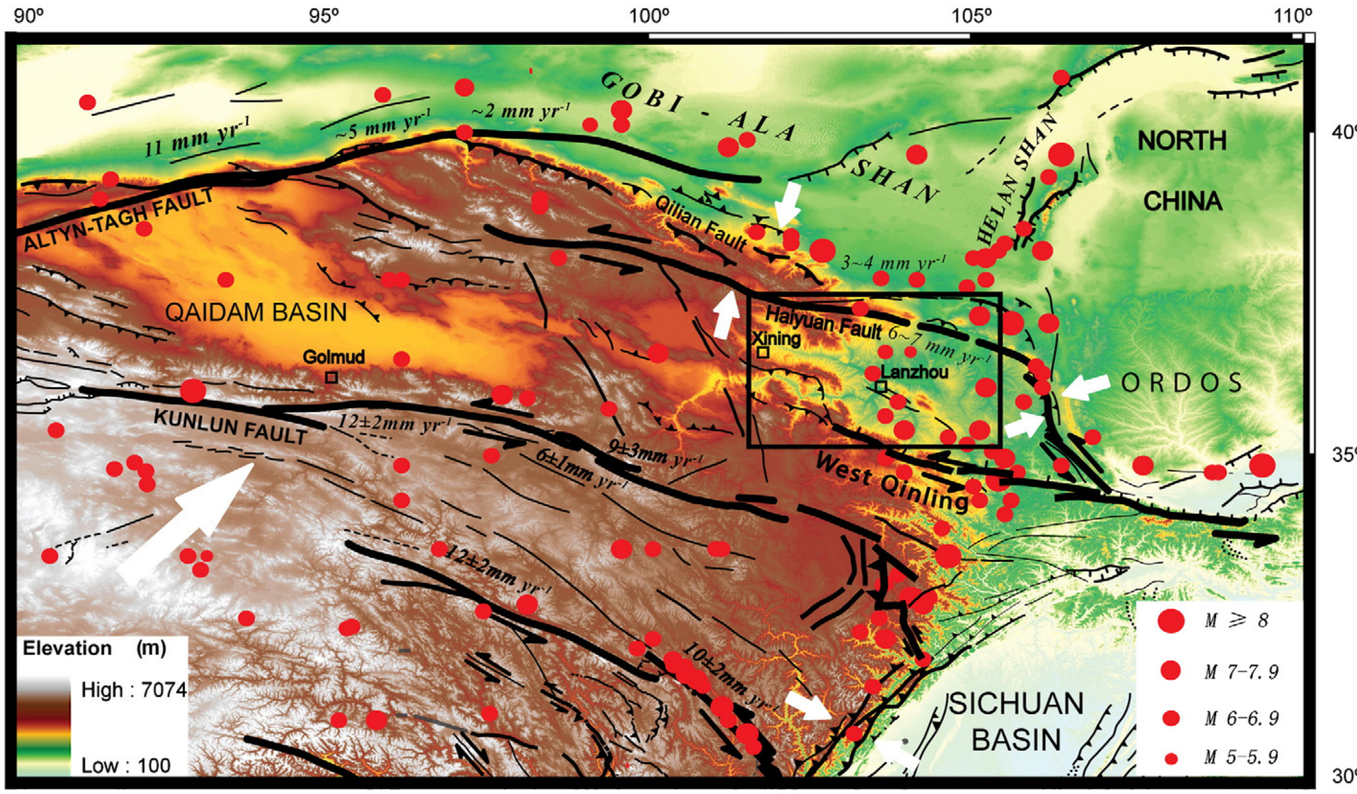

Fig. 1. Distribution of main active faults and historical earthquakes located in the northeastern margin of the Tibetan Plateau. Black lines represent the main active faults, and red circles indicate historical earthquakes ($M \geq 5.0$) recorded during 193 BC to 1995 AD. Black rectangle: location of Fig. 2.
Modified after Xu et al., 2010.

of these data with field validation is still necessary, and they may be used to examine the usefulness of the geomorphic indices. The objective of this paper is to analyze *HI* and *SL* together with leveling data and river incision rates for better understanding of the pattern of neotectonic activities in the study area.

2. Northeastern margin of the Tibetan Plateau

Due to the Indian–Eurasian collision, the NETP is one of the most tectonically active regions in the world. The collision and convergence have resulted in shortening, folding, reverse faulting and lateral thrusting (Fig. 1), and the tectonic evolution of the region has been intensively discussed, which can be summarized as follows. (i) The region experienced three stages of uplift including the Qingzang Movement (three substages commencing at 3.6, 2.5 and 1.70–1.66 Ma), the Kunhuang Movement (three substages commencing at 1.1, 0.8 and 0.6 Ma), and the Gonghe Movement at ~0.15 Ma (Li and Fang, 1999). (ii) The region underwent a progressive plateau rise during the Pliocene and Quaternary, and merged into the Tibetan Plateau (Tapponnier et al., 2001). (iii) The deformation of the NETP initialized in the middle Miocene (George et al., 2001), when it experienced rapid uplift around 8 Ma (Molnar et al., 1993). The Cenozoic evolution of this region is still under debate.

Tectonic activity in the region has been continuing and localized mainly along arcuate faults. Two severe earthquakes have occurred near the study area: (i) an $M = 8.6$ earthquake in 1920 generated by the Haiyuan fault (HYF; Meyer et al., 1998; Ding et al., 2004) with a 250 km surface rupture and a 10 m left lateral displacement, and (ii) the Gulang earthquake ($M = 8.0$, 1927 AD) that caused six segments of surface rupture, located between the Qilian fault zone and the Alashan basin (Yan et al., 2008). Additionally, three $M > 7.0$ and nine $M > 6.0$ earthquakes occurred in the study area between 193 BC and 1990 AD (Fig. 2). Global positioning system (GPS) measurements indicate that the region is moving eastward at a rate of 6–8 mm yr^{-1} (Zhang et al., 2004), and the mean shortening rate of the NETP is >15 mm yr^{-1} for the last 10 Ma (Tapponnier et al., 2001). The faults converging towards the southeast suggests either eastward extrusion or a broad left-lateral WNE–ESE-oriented shearing component (Burchfiel et al., 1991; Zhang et al., 1991; Meyer et al., 1998; Tapponnier et al., 2001).

The Neogene strata consist of red sandstone, which is widely spread over the area with thicknesses of 1600 m in the Linxia basin and 2000 m in the Lanzhou basin (Li et al., 1996). Quaternary sediments including loess, fluvial deposits and lake deposits reach a maximum thickness of 400 m. Tectonic activity is recorded in the Holocene fluvial fan in the West Qinling fault (WQLF), where vertical fault displacement could reach 1.0–2.0 m (Li et al., 2006). At the northern Maxianshan fault (MXF), its scarp on the lowest terrace is 1.0–1.9 m in height (Yuan et al., 2002).

The Yellow River is the largest river in northern China, flowing generally in a northeasterly direction through the NETP and traversing a series of linear mountain belts (Fig. 3). The river has cut deeply (>600 m) into the basins and bedrock ranges (Craddock et al., 2010). The course of the Yellow River was influenced by deformation of the NETP due to the collision of the Indian and Eurasian plates (Li et al., 1997; Lin et al., 2001; Wang et al., 2010) and is deflected in a left lateral sense by approximately 90 km where it crosses the HYF (Gaudemer et al., 1989) (Fig. 3). The stream channel was also horizontally displaced by the WQLF with a maximum of 500 m (Li et al., 2006). The terraces along the main stream cover a time span of approx. 1.8 Ma to a few thousand years (Li et al., 1997; Craddock et al., 2010), indicating the recent uplift in the area.