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Controls on decadal erosion rates in Qilian Shan: Re-evaluation and new insights into landscape evolution in north-east Tibet

Wang Yizhou *, Zhang Huiping, Zheng Dewen, Zheng Wenjun, Zhang Zhuqi, Wang Weitao, Yu Jingxing

State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing 100029, China

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ABSTRACT

Available data from the Qilian Shan in north-east Tibet suggested that decadal-scale erosion rates were closely correlated with local topographic gradient, but not with climatic factors. However, a climatic change to more arid condition was proposed to explain the discrepancy between short-term and long-term erosion rates. In order to re-evaluate the topographic, tectonic and climatic influences on erosion, we adopted five parameters (slope, mean local relief, historical cumulative seismic moment, runoff coefficient of variation and fault density) to study 11 drainage basins in north-east Tibet. Our results showed that terrain gradient, rock fracture density and rainstorm intensity had strong influence on erosion rates while 60-year cumulative seismic moments of historical earthquakes showed weaker correlations. There was a spatial variation in the erosional mechanisms across the basin, with detachment-limited dominance around the ridges (slope >20°) and deposition dominant in the flat areas. The variation may lead to the discrepancy between short-term and long-term erosion rates. In general, our study supports the 'bath-tub' model for low relief intermountain basins, hence providing new insights into the landscape evolution of the Qilian Shan in northeastern Tibetan Plateau.

1. Introduction

Landscape evolution of an active mountain can be described as a competition between tectonic processes that elevate topography and erosion that destroys it (Burbank et al., 1996; 2003; Molnar et al., 2006; Reiners and Brandon, 2006; Molnar et al., 2007; Champagnac et al., 2012). In the dynamic process, tectonics, climate and erosion are often interlinked and play critical roles. For example, horizontal compression can cause crustal thickening which then raises earth's surface via isostatic compensation. A rising landscape would increase orographic precipitation, leading to higher erosion rates; in turn, high and focused erosion rates may change the structural pattern (Dahlen and Suppe, 1988; Willett, 1999; Beaumont et al., 2001; Willett and Brandon, 2002; Reiners et al., 2003; Roe et al., 2008). Tectonics can also fracture rock, which helps to increase erosion rates. Furthermore, the focused erosion due to river or glacier carving will drive the isostatic uplift of rocks, and possibly surface uplift of peaks and ridges (Wager, 1937; Holmes, 1944, 1965; Molnar and England, 1990).

Erosional processes are controlled by multiple factors such as tectonics, lithology, climate, and topography. However, how these factors affect erosion remains a puzzle (Champagnac et al., 2012). Many suggest that the topographic variables, such as average slope (Aalto et al., 2006), local relief (Ruxton and McDougall, 1967; Montgomery and Brandon, 2002; DiBiase et al., 2010; Portenga and Bierman, 2011), local curvature (Roering et al., 1999), basin relief ratio (Summerfield and Hulton, 1994), and catchment size (Milliman and Meade, 1983; Milliman and Syvitski, 1992), play the most important role. Indeed, all these factors are associated with the steepness of terrain, and indicate that on a short time scale, steep slopes lead to higher erosion rates. However, in the long run, erosion may result in increased relief as localized along the river channel. Meanwhile, the background erosion rate is uniform across the landscape, hence not changing the relief (Champagnac et al., 2014). Therefore, it is difficult to conclude whether it is the terrain steepness that leads to higher erosion or the erosional processes that increase the relief. At the same time, climatic variables such as precipitation, discharge, and runoff can also play key roles in the short-term erosion process (Galy and France-Lanord, 2001; Gabet et al., 2008). In addition, the degree of rock fracturing (Burbank et al., 1996; Molnar et al., 2007; Clarke and Burbank, 2010), the historical seismicity and storm-driven runoff variability (Dadson et al., 2003) also affect the decadal erosion rates.

Among the active growing plateau margins, the northeastern Tibetan Plateau is considered to be one of the youngest fronts (Tapponnier et al., 2001). Learning the erosion distribution and rates is key to understanding how the topography, climate, tectonics, and lithology have interacted. Pan et al. (2010) presented decadal erosion rates of 11 drainage basins and suggested strong correlations with slope and mean local relief, but weak correlations with precipitation, temperature, discharge, and runoff. However, some other aspects still need to be explored, such as how to quantify the modern tectonic scenarios, lithology, storm and terrain steepness among the Qilian Shan, whether these variables

* Corresponding author. Tel.: +86 18810404633.
E-mail address: wangyizhou.-123@163.com (W. Yizhou).

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contribute to short-term catchment erosion, and whether there is any spatial difference of erosion within the drainage basins.

In order to answer these questions, we first quantify the potential variables related to erosion. We take historical cumulative seismic moments as a proxy for tectonic movement; the runoff coefficient of variation for climate; fault density for lithology; and mean local relief and slope for topography. Then we carry out correlation and regression analyses for catchment-wide decadal erosion rates based on the work of Pan et al. (2010) with all variables to determine which potential variables might contribute more to erosion rates.

2. Regional setting

The Qilian Shan extends from 95°E to 103°E, and 37°N to 41°N (Fig. 1), and bounds the northeastern Tibetan Plateau. It trends WNW-ESE, stretches over 1000 km long, and is about 300 km wide. Peaking at about 5500 m, the Qilian Shan has a mean elevation of 4000 m between its front and the northern margin of the Qaidam Basin (Fig. 1). To the south, the mean elevation of the Qaidam Basin is about 3000 m, with local topographic relief around 300 m. To the north, the Hexi Corridor basin overlies the stable Alashan block with a lower surface elevation of 1500–2000 m. The present climate environment here is arid to semiarid, and the temporal–spatial difference of precipitation is relatively large (Zhang et al., 2011; Niu et al., 2012). Many inland rivers, the Danghe, Shule, Heihe, and Shiyang Rivers, which originate from high altitude areas, incise the steep margins of the Qilian Shan, and flow into the Hexi Corridor and its flanking basins (Zhang et al., 2012). Cenozoic exhumation of the Qilian Shan has produced a kilometer-thick coarsening-upward succession of lacustrine–fluvial deposits in the Hexi Corridor basin to the north and the Qaidam basin to the south. The rivers are still active and transport a great amount of sediment to the flanking basins (Pan et al., 2010). All these observations indicate that erosion and deposition around the Qilian Shan have controlled the Late Cenozoic landscape evolution.

Devonian to Cambrian metamorphic rocks form most of the bedrock of the Qilian Shan, and have deformed since the early Paleozoic (Song et al., 2003). The Mesozoic was dominated by the subsequent extension, as evidenced by the widespread deposition of Jurassic and Cretaceous continental sediment in the region (Vincent and Allen, 1999). Since the early Cenozoic, the reactive Qilian Shan orogenic belt has been undergoing contractional deformation which continues to today (Institute of Geology, China Seismological Bureau and Lanzhou Seismological Institute, 1993; Meyer et al., 1998; Yin et al., 2008). The Cenozoic tectonics around the Qilian Shan is characterized by folding, thrust faulting, and strike-slip faulting that accommodates part of the India–Eurasia plate convergence (Tapponnier et al., 1990; Yuan et al., 2011, 2013; Zheng et al., 2013). The presence of Quaternary folds and thrust faults (Tapponnier et al., 1990; Meyer et al., 1998), the distribution of historical and instrumentally located earthquakes, and thrust fault-plane solutions (Molnar and Lyon-Caen, 1989) collectively indicate that the ranges of the Qilian Shan are still growing as a result of shortening of the crust. Geodetic shortening rates between the Qaidam and Alashan block are determined to be 5–7 mm a^{-1} by GPS (Zhang et al., 2004), and active shortening deformation is distributed throughout the 270 km wide Qilian Shan plateau (Institute of Geology, China Seismological Bureau and Lanzhou Seismological Institute, 1993; Métivier et al., 1998; Hetzel et al., 2004; Champagnac et al., 2010; Yuan et al., 2011, 2013).

3. Methods

In order to understand what contributed to the erosional processes, we compared the data on several parameters related to tectonics, climate, lithology, and topography, with decadal erosion rates from Pan et al. (2010) and ran a regression to find the most important factor.

3.1. Drainage basins and decadal erosion rates

The decadal erosion rates of the 11 subbasins of the Danghe, Shule, Heihe and Shiyang Rivers were estimated using the annual sediment load including suspended load, estimated bed load and dissolved load (Pan et al., 2010). All the data were documented at relevant hydrological stations from the 1950s to 2000s (Pan et al., 2010). The erosion rates of each basin were listed in both Pan et al. (2010) and Table 1.

Drainage basins, associated rivers, and their topographic characteristics were extracted from the SRTM digital elevation model (DEM), with a resolution of 90 m (Farr et al., 2007; Fig. 1), using the Hydrology toolbox in the ArcGIS 9.3 software.

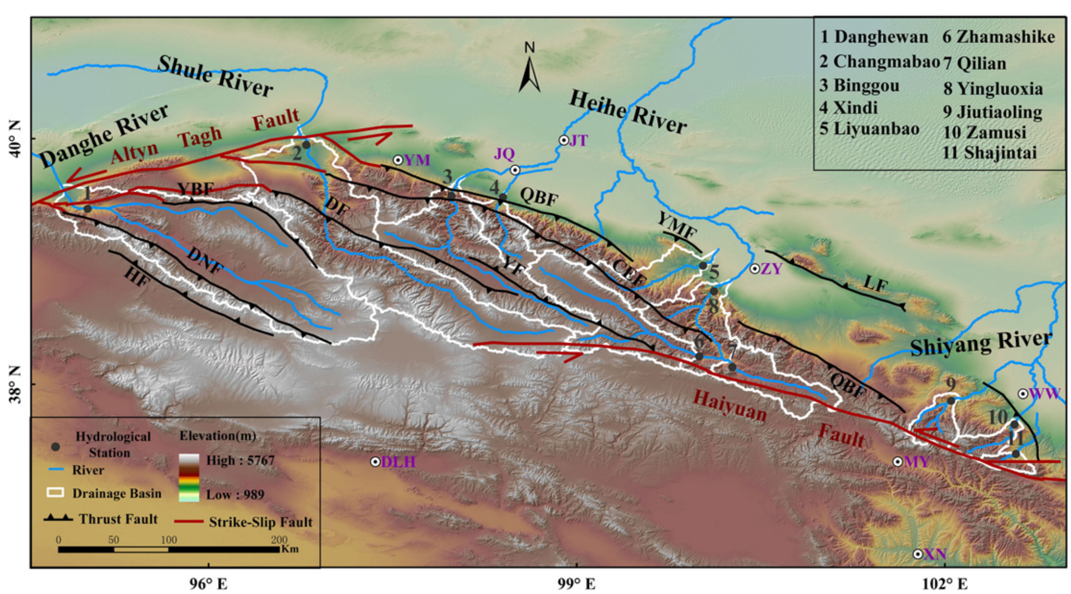

Fig. 1. Shaded-relief map of the Qilian Shan. HF – Houtang Fault, DNF – Danghe Nanshan Fault, YBF – Yemahe North Margin Fault, DF – Daxueshan Fault, YF – Yin'aocao Fault, CEF – Changma-Ebo Fault, QBF – Qilian Shan North Margin Fault, YMF – Yumushan Fault, LF – Longshoushan Fault, WTF – Wuwei-Tianzhu Fault. YM – Yumen, JT – Jinta, JQ – Jiuquan, ZY – Zhangye, WW – Wuwei, DLH – Delingha, MY – Menyuan. Rivers are shown in blue lines with 11 hydrological stations whose names are listed in the legend. The outlines of drainage basins are shown in white lines.