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Soft sediment deformation structures in the Lixian lacustrine sediments, eastern Tibetan Plateau and implications for postglacial seismic activity

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ABSTRACT

The eastern margin of the Tibetan Plateau is characterized by frequent earthquakes, which are closely associated with tectonic activity. To assess tectonic activity during the Late Pleistocene, we studied a well-exposed, 23-m-thick lacustrine sequence on the eastern margin of the plateau and found a variety of soft-sediment deformation (SSD) structures. Distributed in 24 stratigraphic levels, they comprise clastic dykes, ball-and-pillow structures, flame structures, clastic gravels, micro-faults, and slump folds. Most of the SSD structures indicate deformation mechanisms related to liquefaction and/or fluidization processes, most probably triggered by paleoseismic events. Given at least 4 historical earthquakes of $M > 7$ in the study area, most SSD structures in the Lixian lacustrine sequence indicate seismic events with $M > 6$ while simple flame structures point to some lower-magnitude earthquakes. OSL dating indicates that the sequence accumulated between 15.8 and 6.0 ka, giving a mean recurrence interval of 480 years for the 24 events, and demonstrating that lacustrine sediments in eastern Tibet have the potential to record a continuous seismic history on the centennial scale.

1. Introduction

Since the initial collision between India and Asia in the Early Cenozoic (65–55 Ma, e.g. Jaeger et al., 1989; Ding et al., 2005; Mo et al., 2008; Yi et al., 2011), the region has experienced strong thrust compression, lateral extrusion, and clockwise rotation (e.g. Zhang et al., 2004; Liang et al., 2013), resulting in crustal shortening and mountain uplift in and around the Tibetan Plateau. Geomorphic evidence of crustal deformation in central Nepal suggests that thrusting along the Main Frontal Thrust has absorbed 21 ± 1.5 mm/year of N–S shortening on average through the Holocene (Lave and Avouac, 2000). On the eastern margin of the plateau, the Longmen Shan belt has experienced horizontal shortening of 3–4 mm/year and uplift of 3.5 mm/year (Deng et al., 1994; Wang, 2009) or 2–3 mm/year (Liang et al., 2013). These tectonic movements are responsible for frequent earthquakes in and around the Tibetan Plateau.

Analysis of instrumental data since AD 1900 indicates that the Tibetan Plateau experienced three phases of strong ($M \geqslant 7$) earthquake clustering: the Haiyuan-Gulang earthquake series in 1920–1937, the Chayu-Dangxiong series in 1947–1976, and the Kunlun-Wenchuan series from 1995 to the present (Deng et al., 2014). Each phase is composed of at least one seismic event of $M \geqslant 8.0$ and several $\geqslant 7.0$ (Fig. 1). Each has its own major active region, which gives its name to the series (Deng et al., 2010). However, seismic data before AD 1900 remain sporadic and discontinuous, which hinders the statistical analysis of seismic activity in and around the Tibetan Plateau.

The eastern margin of the Tibetan Plateau is characterized by a monsoon climate, frequent earthquakes, and a landscape of alpine valleys. The East Asian summer monsoon has a major influence on vegetation cover and fluvial development (e.g. Bookhagen and Burbank, 2010; Liu-Zeng et al., 2011; Jiang et al., 2015). Large amounts of sediment from coseismic landslides are removed by rivers (e.g. Liu-Zeng et al., 2011; Wang et al., 2015), but high precipitation alone cannot fully account for the rapid erosion. Recent studies indicate that tectonic activity characterized by frequent earthquakes may have had a major role on erosion on the eastern margin of the Tibetan Plateau, while the climatic influence seems minor (Ouimet, 2010; Li et al., 2015; Liang and Jiang, in press). Rapid erosion results in extensive exposure of old rocks, such as Silurian and Devonian phyllite interbedded with metasandstone, Carboniferous and Permian limestone interbedded with phyllite, Triassic metasandstone interbedded with phyllite, and Yanshanian granite, diorite, and syenite. In comparison, Quaternary clastic deposits are sporadically distributed (Fig. 2). On the other hand, long-term anthropogenic forcing of soil erosion occurs at large catchment scales with an area of more than 100,000 km^2 (e.g. Lu and Higgitt, 1998; Chen et al., 2001; Lu et al., 2003). All of these factors make it difficult to investigate palaeoearthquakes by trenching in this tectonically active region.

Numerous dammed lakes in the study area probably preserved a record of tectonic activity, such as soft-sediment deformation (SSD)

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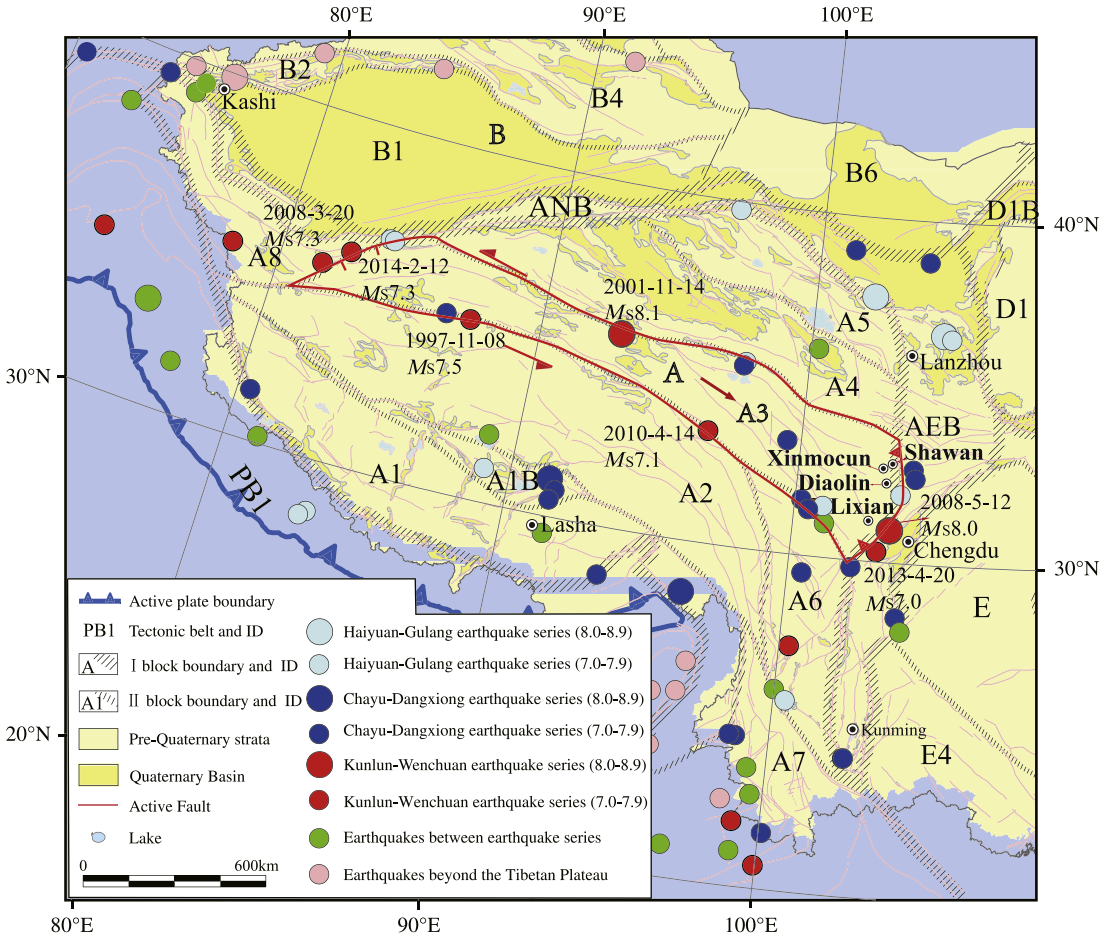

Fig. 1. Active tectonic regionalization and earthquakes of $M \geq 6$. The 1970–2012 seismicity data are from the China Earthquake Data Center (http://data.earthquake.cn/data), and the 1900–1970 seismicity data are from the Department of Earthquake Disaster Prevention of China Earthquake Administration (1995).

structures and variations in geophysical and geochemical proxies (e.g. Wang et al., 2011; Jiang et al., 2014; Xu et al., 2015; Liang and Jiang, in press). These studies have focused on seismic events in marine isotope stage 2 (MIS 2, 27–10 ka) and SSD structures are dispersed at different sites. We have studied SSD structures in a thick (>23 m), well-exposed lacustrine sequence on the eastern margin of the Tibetan

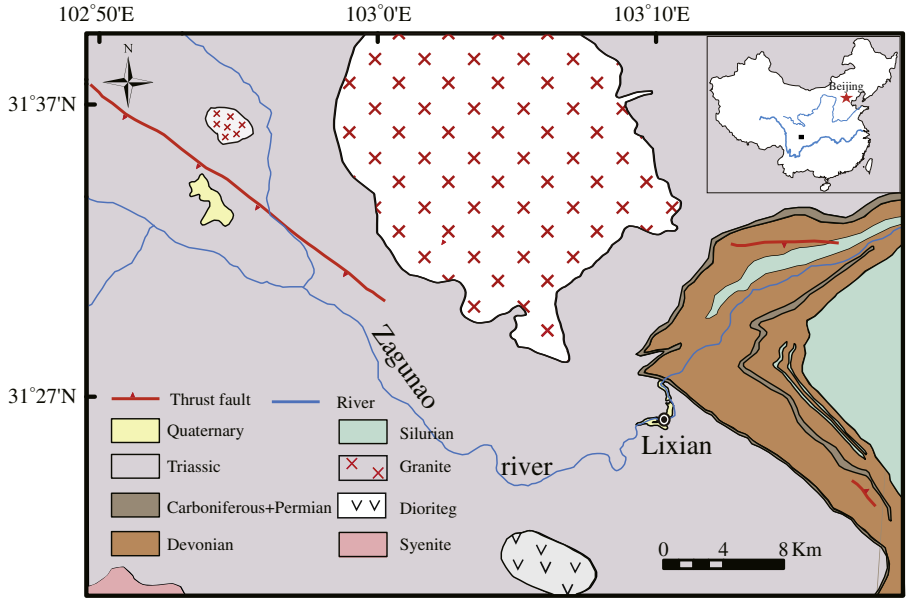

Fig. 2. Geological map of the study area and location of the Lixian lacustrine section.