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Uplift of the Tibetan Plateau and its environmental impacts

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The Tibetan Plateau (TP), also known as the Qinghai–Xizang Plateau in Chinese, is the highest plateau on Earth. It constitutes a classic case study for validating the theory of continental convergence, and in addition its uplift is one of the most significant global geological events of the Cenozoic era (Tapponnier et al., 2001). The uplift of the TP, together with the associated tectonic movements of the surrounding regions, has not only played an extremely important role in Cenozoic climatic evolution, but also had significant effects on the regional environment. These effects are especially important in the inland aridification of Asia, the evolution of the monsoon and the formation of the cryosphere (Qiu, 2010; Yao et al., 2012a), but there are other regional and global influences, too (Li, 1991). In particular, the uplift of the TP has fundamentally influenced the vegetation and fauna there, and also the cultural evolution and social development of humans. Because of the profound importance of the Tibetan uplift, during the past few decades scholars from around the world have been inspired to devote significant amounts of time to studying its many aspects.

This special issue of *Quaternary Research* presents recent achievements of the study of the environmental and climatic changes associated with the uplift of the TP. The articles are by the students and colleagues of Jijun Li, and by Li himself. They result from Li's pioneering work on Tibet and from the decades-long follow-up by Li and the research community he inspired. The fourteen papers included here are developed from oral and poster presentations in the International Symposium on *the Uplift of the Qinghai–Tibetan Plateau and its Social and Environmental Impacts: Celebration of Professor Jijun Li's 80th Birthday and His Academic Achievements*, held at Lanzhou, China, 9–10 October, 2012. The symposium received over a hundred abstracts and papers, of which 31 Chinese papers were previously published in 2013 in two Chinese journals, namely the *Journal of Lanzhou University (Vol. 49)* and *Marine Geology* & *Quaternary Geology (Vol. 33)*. The 14 papers in this special issue of *Quaternary Research* cover various aspects of the uplift of the TP and its environmental effects in the extended areas around the TP (see Fig. 1 for the locations).

They are all original research papers, with the exception of the lead paper of the Special Issue, which is a review of the step-wise uplift hypothesis of Li et al. (1979) in the northeastern TP. Based on content, the 14 papers can be broadly categorized into the following themes:

1) *Uplift, tectonic activity and long time-scale climatic changes*. Four papers fall within this category. Professor Li is one of the earliest researchers in China to set foot in the field and has made contribution to the duration, amplitude and nature of the TP uplift and its influence on the Asian environment during the Quaternary. He is also the first scientist in the world to propose the hypothesis of two periods of planation and three periods of uplift for the evolution of the TP. In the lead article, Li and co-authors. present a comprehensive review of the stepwise rapid-uplift hypothesis based on work collated from several decades of their publications, both in English and Chinese. They further discuss the Late Miocene–Quaternary uplift of the northeastern Tibetan Plateau and the resulting response of the Yellow River, confirming that the plateau started rising mainly after 8 Ma and that a series of major tectonic movements occurred after 3.6 Ma.
   Chang et al. present the chronological and sedimentation rate changes recorded in a 751.98 m deep drilling core from the eastern Tarim Basin, north of the TP (Fig. 1). They found that as a result of regional tectonic movement, since ~5.39 Ma the sedimentation rate in the

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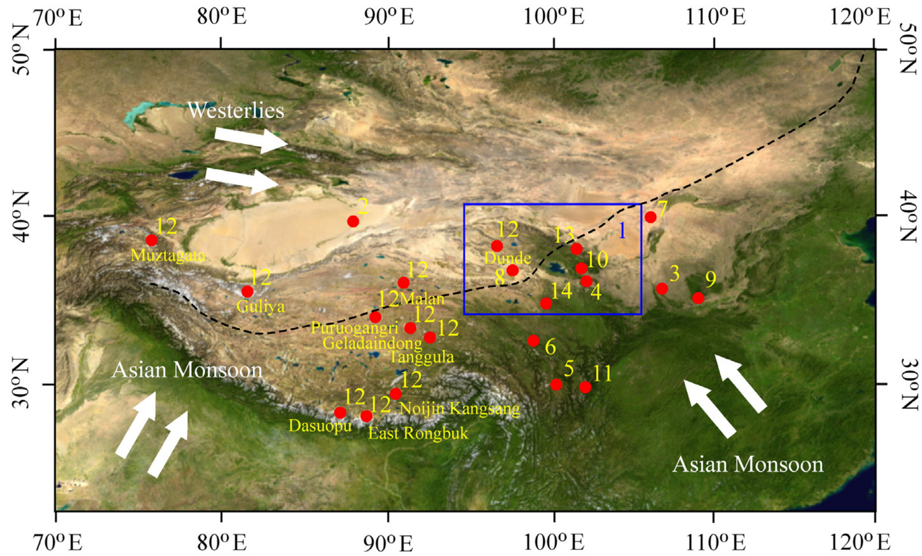

Fig. 1. Remote-sensing image of the Tibetan Plateau and surrounding regions. The dash line shows the summer monsoon limit across the TP according to Chen et al. (2008b). The locations studied by the papers in this special issue are indicated by red dots. 1—Li et al. for the uplift of the northeastern TP shown in the box, 2—Chang et al. for East Tarim, 3—Song et al. for the Chaona loess, 4—Dong et al. for Jishi Gorge of the Yellow River, 5—Xu and Zhou for the Yazheku River near Daocheng Ice Cap, 6—Ou et al. for late Quaternary glacial history in the eastern TP, 7—Chen et al. for the Ulan Buh Desert evolution, 8—Yu et al. for moisture changes in Qaidam Basin, 9—Xia et al. for Holocene asynchronous monsoon history, 10—Gou et al. for last millennium moisture change, 11—Deng et al. for summer temperature changes, 12—Yang et al. for oxygen isotope changes in the ten ice cores marked beside the site number, 13—Cao et al. for the fluctuations of existing glaciers in the Qilian Mountains, and 14—Wang et al. for topsoil erosion in the northeastern TP.

eastern Tarim Basin decreased dramatically at 1.77 Ma from about 185 m/Ma to 40 m/Ma, providing further evidence of the rapid uplift of the northeastern Tibetan Plateau during this period, as proposed by Li et al. in this issue.

Using rock-magnetic proxies from a Quaternary loess–paleosol sequence in the Central Chinese Loess Plateau, Song et al. report new findings about the Middle Pleistocene Transition, which began at ~1.26 Ma and ended at ~0.53 Ma. The long transition recorded in the section is attributed not only to orbital forcing, but also to the rapid uplift of the Tibetan Plateau in the middle Pleistocene.

In the final paper of this group, Dong et al. report an ancient landslide that dammed the upper reaches of the Yellow River on the northeastern Tibet Plateau. Based on both radiocarbon and OSL dates, they suggest that the landslide occurred at around 8100 cal yr BP, was breached between 6780 cal yr BP and 5750 cal yr BP. The landslide was not responsible for the devastation of the Lajia site, a notable Neolithic village at the margin of the northeastern TP, which was buried by an unexpected abrupt catastrophic event (Lu et al., 2005), and for which the landslide was long blamed.

2) *Late Quaternary glacial history*. TP glaciation has attracted the interest of many researchers since the 1920s. Rigorous study was started in the early 1970s by a group of Chinese scientists including Professor Jijun Li, and many of their preliminary results were published both in Chinese and English (e.g., Li, 1996). The glacial history of the TP is still an active research topic, and two papers report on late Quaternary glacial activity and related landforms in the eastern TP, based on optically stimulated luminescence (OSL) and electron spin resonance (ESR) dating methods.

Xu et al. propose a model of glacial fluvial terrace formation in the area of the Yazheku River, originating from the Daocheng Ice Cap, eastern Tibetan Plateau. The fluvial sequences are dominated both by glacial–interglacial cycles and by strong tectonic uplift. Based on ESR dating and analysis of sedimentary characteristics, the proposed model demonstrates that strath terraces were created during glacial expansions, with aggradation filling the valley during deglaciation, and being incised to form terraces during the succeeding interglacial period. It was previously reported that serial glacial moraines existed in the valleys of the Hengduan Mountains (Li, 1996).

Ou et al. use OSL methods to date the five series of moraines in the Yingpu Valley, the Queer Shan ranges of Hengduan Mountains, eastern TP. They conclude that the five series of moraines only formed, respectively, during the cold periods in the Little Ice Age, the Late Holocene, Late Glacial, the global Last Glacial Maximum (LGM) and marine oxygen isotope stage 3, rather than during episodes of enhanced summer monsoon and moisture.

3) *Desert evolution, climatic and environmental changes*. The significance of the uplift of the TP is not only limited to the questions of the plateau itself, but also to the surrounding regions that the plateau has fundamentally affected. Aeolian processes, desertification and desert development, which is strongly influenced the regional economic and social development of the western China under increasing global warming and human impact (Qin et al., 2002), are the major consequences of the uplifted TP, due to changes to climate and environment. In this special issue, three papers use aeolian and desert sedimentary records to reconstruct desert evolution, and climatic and environmental changes during the late Quaternary and Holocene.

Based on three drilling cores, Chen et al. present the evolution history of the Ulan Buh desert, northeast of the TP and south of the Mongolia Plateau. They found that the present desert landforms only formed after ~90 ka, following the disintegration of the Jilantai–Hetao Mega-paleolake (Chen et al., 2008a).

Yu and Lai used OSL to date aeolian loess and desert sand deposits in the Qaidam Basin in the northeastern TP and a major source of dust storms (Chen et al., 2013). They constructed an effective moisture index from aeolian sediments in order to trace Holocene moisture changes in the basin and found that the climate was relatively humid and stable from 8.3 to 4.4 ka. They deduced that effective moisture change in the basin during the Holocene was mainly controlled by the Asian summer monsoon.

Xia et al. present a high-resolution multi-proxy record from a 3.2-

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m-thick loess–paleosol sequence in the southern Chinese Loess Plateau and from which they construct a summer monsoon index and a winter monsoon index. They found that the Holocene climatic optimum there occurred in the mid-Holocene, when the winter monsoon intensity declined to a minimum, suggesting that the East Asian summer and winter monsoons varied asynchronously during the Holocene.

4) *Variations of climatic indicators associated with the TP*. Temperature and precipitation changes in the TP are of significant interest to the international scientific community. In this issue five papers are concerned with annual moisture and temperature variations over the last 1000 years and the last 100 years based on tree-ring and/or ice-core isotope data.

Gou et al. use tree-ring data to reconstruct precipitation variations over the past millennium in the northeastern TP. They show that there were four decade-long droughts similar to or even more severe than the drought in the 1920s, a major drought event which resulted in millions of deaths in the semi-arid and arid northern China (Liang et al., 2006).

Deng et al. present a tree-ring reconstruction of June–July temperature from the southeastern TP from AD 1446 to 2008. The reconstruction shows that there were six decades-long warm periods. The last warm period was from AD 1927 to 2008 and was not as warm as the period from AD 1525 to 1598. The two papers indicate that the climate in the monsoon-dominated region of the TP (Chen et al., 2008b) was possibly influenced by ENSO, the Pacific Decadal Oscillation and by solar activity. Ice-core records from the TP are valuable climatic indicators which can provide long, high-resolution climatic information in low latitudes of the northern hemisphere (Qin et al., 2000; Thompson et al., 1989; Yao et al., 1997).

In this special issue, Yang et al. present annual $\delta^{18}O$ variations of ten ice cores from north to south across the westerly- and monsoon-dominated parts of the TP (Fig. 1; Chen et al., 2008b). The results demonstrate that $\delta^{18}O$ values generally increased during the past century. The increase was the largest in the northern TP, moderate in the central part and the lowest in the southern TP. Validation of the ice core $\delta^{18}O$ temperature significance with ground station data throughout the TP indicates both a close relationship between the ice-core $\delta^{18}O$ and temperature in the northern TP and the possible perturbation of ENSO activities on the presentation of the ice-core temperature signal in the southern TP.

The climatic controls on $\delta^{18}O$ in precipitation over the Tibetan Plateau are further reviewed by Yao et al. (2013). Their results may provide a basis for improved temperature reconstructions from ice-core $\delta^{18}O$ data from the TP. Modern glaciers in the TP are retreating rapidly (Qin et al., 2000). But due to different atmospheric circulation patterns over the TP in terms of the monsoon and westerly dominance the variation rates of glacial mass balance vary from region to region across the TP (Yao et al., 2012b), leading to different discharge of the rivers originating from the TP.

In the fourth paper, Cao et al. use topographic maps, multispectral satellite data and Real-Time Kinematic GPS data to analyze glacier changes in the eastern Qilian Mountains under the present global warm climatic regime. These glaciers are important because they provide water resources to the oasis along the Hexi Corridor, the traditional Silk Road, and to the desert area of western China. Cao et al. found that all of the glaciers they studied underwent a general retreat and thinning between 1972 and 2010, the rate of retreat being $2.4–6.6 \pm 1.5$ m yr^{-1}.

Soil erosion is one aspect of the serious land degradation occurring at high elevations of the TP. In the final paper, using ^{137}Cs measurements, Wang et al. studied topsoil erosion rates under different conditions in a catchment in the source region of the Yellow River in the northeastern TP, and found that soil erosion rates vary with vegetation coverage and that severe erosion occurs mainly in the topsoil (0–10 cm).

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