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Consistent vegetation and climate deterioration from early to late MIS3 revealed by multi-proxies (mainly pollen data) in north-west China

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ABSTRACT

Pollen data are useful palaeoecological archives for understanding vegetation and associated climatic changes. In this paper we present new pollen data and other proxies (lithology, grain size, loss-on-ignition (LOI_{org} at 550 °C)) obtained from a sediment core (BLK11A) from Balikun Lake, north-west China, to explore the vegetation and climate history of 60.4–27.3 ka (1 ka = 1000 calendar years before AD 1950), covering Marine Oxygen Isotope Stage (MIS) 3. Our three main results are: 1) a high relative abundance of thermophilous temperate tree pollen (e.g. *Betula*) accompanied by other warm-wet associated species (e.g. Ranunculaceae, Cyperaceae, *Typha*) suggesting warm and wet climate conditions during most of the early MIS3 (59.0–51.7 ka) that resemble the "Holocene optimum" with an increase in effective moisture in most parts of arid western China. Watershed bio-productivity was high as represented by the high LOI_{org} value. A high abundance of *Ephedra* pollen was assumed to be caused by frequent shifts in lake level, with locally favourable habitats (dry lake beds) forming when lake area shrank. In addition, an interval with deteriorated climate and vegetation was found between 57 and 56 ka, with a sharp decrease of vegetation cover and bio-productivity. 2) The middle to late MIS3 (51.7–27.3 ka) was marked by the development of desert shrubs (e.g. Rhamnaceae, *Nitraria*, *Zygophyllum*), together with low pollen concentrations of upland communities, indicating a continuous and gradually cooling and drying climate that resulted in reduced vegetation cover. Deterioration of the climate is also suggested by the presence of halite deposits and a sustained decrease in watershed bio-productivity. 3) The regional vegetation around Balikun was mainly dominated by *Artemisia* and Amaranthaceae, which are typical desert-steppe and/or desert taxa, indicating a progressive aridification in north-western China in the late Quaternary. Our new interpretations contradict earlier inferences of highest lake level and wettest conditions prevailing during the late MIS3, and we propose that the decline of northern high-latitude summer insolation and the increase of global ice volume from early to late MIS3 have exerted a remarkable influence on the evolution of vegetation communities and lake level in arid western China on orbital or sub-orbital time scales.

1. Introduction

Arid western China (Fig. 1), mainly dominated by the Westerlies at present, is one of the driest regions in the world, with scarce water resources, sparse vegetation cover, and vulnerable ecosystems (Qin et al., 2005; Narisma et al., 2007). The stochastic climate-controlled rainfall inputs, and losses from evapotranspiration and leakage, control the soil-water availability and hence affect the organisation and functionality of many ecological systems in arid areas (Scholes and Walker, 1993). Even short periods of climate change could exert a profound influence on the hydrological conditions and landscape. For example, the coherent higher annual air temperature and precipitation starting in the 1980s has led to an increase in runoff, a rise in lake-levels, and reduction of sand-dust storm days in this region (Shi et al., 2007). Vegetation communities, as the main biomass in these arid areas, responded directly to variations in the moisture and temperature with an enrichment of vegetation types and increased vegetation cover over the past 20 years in north-western China (Ma et al., 2003; Shi et al., 2007). Significant research efforts have been directed towards investigating the long-term evolution of the vegetation and the climate conditions during the Holocene in arid western China (Herzschuh et al., 2004; Shen et al., 2005; Herzschuh, 2006; Liu et al., 2008, 2015; Tao et al., 2010; Jiang et al., 2007, 2013; Zhao et al., 2007, 2009; Huang et al., 2009, 2015; Luo et al., 2009; Li et al., 2011; Wang et al., 2013). These studies reveal a generally consistent pattern of the development of arboreal vegetation, warmth-loving herbs, and dense vegetation cover as a result of increases in moisture and temperature during the Holocene Optimum

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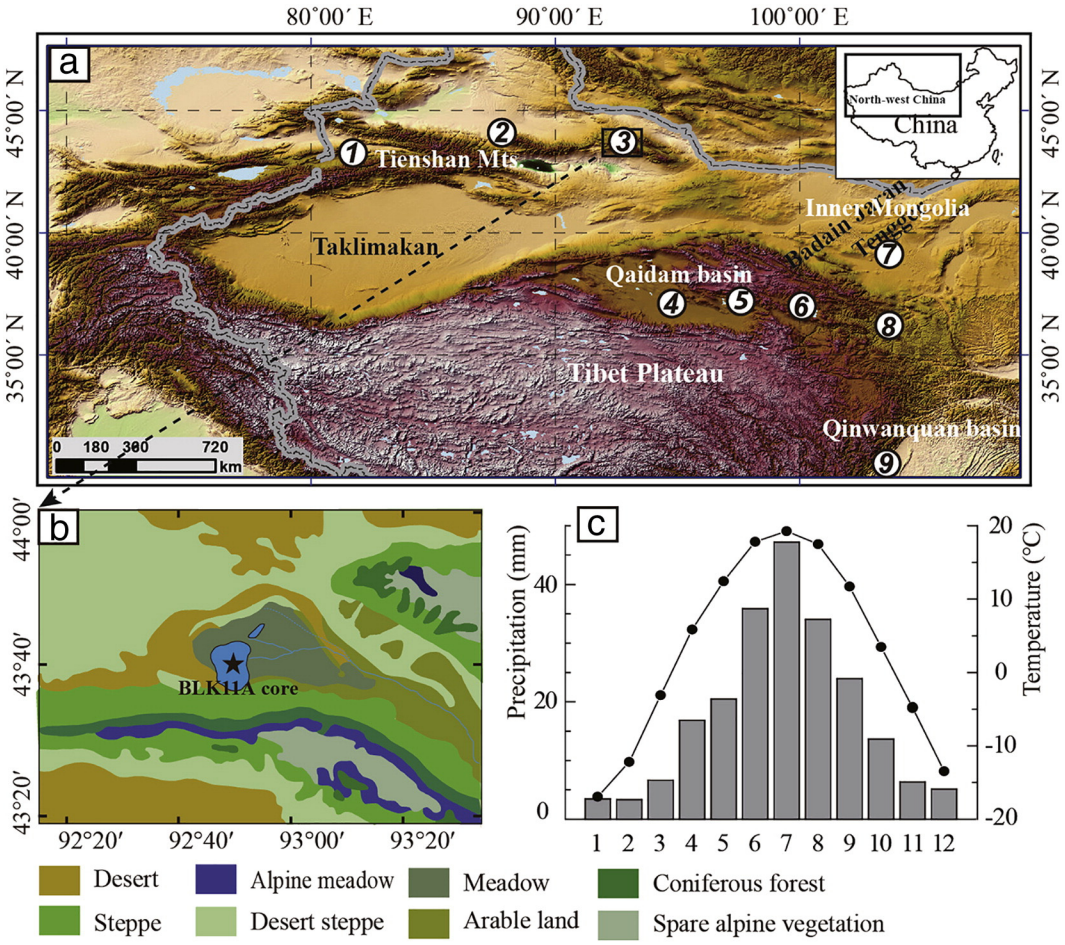

Fig. 1. a) Location of our study area and other palaeoclimate proxy records cited in the text (1: Kesang Cave (Cheng et al., 2012); 2: BYH10 loess from northern slope of the Tienshan Mountains (Li et al., 2016); 3: Balikun Lake (this study); 4: Qarhan Salt Lake (Fan et al., 2014; Wei et al., 2015); 5: Gahai (Fan et al., 2010); 6: Qinghai Lake (Madsen et al., 2008; Liu et al., 2010); 7: Zhuyeze (Long et al., 2012b); 8: Fangjiaping Loess (Jiang et al., 2011); 9: Qinwangchuan Basin (Long et al., 2016). b) Vegetation types of Balikun Basin. The core site, BLK11A, in Balikun Lake is marked by black star. c) Mean monthly temperature and precipitation from Balikun meteorological station for 1958–2003.

(~9–5 ka). Desert shrubs and low vegetation cover characterised the cold and dry periods, such as the Last Glacial Maximum (LGM; Zhao et al., 2015). However, the evolution of vegetation and climate are poorly documented in arid western China at a longer temporal-scale beyond MIS 2, thus our understanding of past arid ecosystems and their responses to changing climate is still insufficient.

MIS3 (~59–29 ka) is an interstadial in the late Quaternary with the characteristics of substantially reduced, although not completely degraded, continental ice sheets that can be compared with the Holocene and present climate (Imbrie et al., 1989; Dansgaard et al., 1993; Voelker, 2002; North Greenland Ice Core Project Members, 2004; Lisiecki and Raymo, 2005). Studies on the absolutely-dated oxygen isotope ($\delta^{18}O$) records of stalagmites from Kesang cave (China) and Tonnel'naya cave (Uzbekistan) reveal a dynamic precipitation history with stalagmite growth during both the early MIS3 and the Holocene, but hiatuses during MIS4, mid to late MIS3, and MIS2, suggesting a wetter early MIS3 and Holocene climate (Cheng et al., 2012, 2016). An alternating pattern from arboreal plants and thermophilous herbs (e.g. Cupressaceae, *Tsuga*, Poaceae, Cyperaceae) to shrubs and cool-adapted herbs from early to late MIS3 was documented using pollen assemblages from loess deposits in north-west China (Jiang et al., 2011). In general, changes in the global climatic boundary conditions (e.g. solar radiation and ice sheets) would first lead to a reorganisation of major atmospheric systems, then foster the evolution of the regional landscape and vegetation by altering the hydrological conditions (Bigelow et al., 2003; Mithen, 2006; Shakun and Carlson, 2009). However, existing studies are faced with problems such as the frequent presence of erosional hiatuses (e.g. Rhodes et al., 1996; Zhao et al., 2013) and uncertainties in the chronology (Lai et al., 2014, Long et al., 2015; Song et al., 2015), especially for terrace and loess deposits. For example, pollen records from Yili Valley reveal that montane forest-steppe with a major component of *Picea* and *Taraxacum* was dominant here during the late MIS3 (Zhao et al., 2013), but Chen et al. (2016) point out that the depositional section consists mainly of fluvial sediments with evidence of a seasonal localised pond environment along a small riverbank, making it difficult to interpret the pollen assemblages as a representative signal of regional vegetation and climate. More detailed long-term palaeoecological studies are needed to assess the spatiotemporal variation in the composition and structure of plant communities under different climatic boundaries and regional hydrological conditions.

Our target lake (Balikun Lake) has continuous Quaternary deposits spanning the Late-Pleistocene interval (Ma et al., 2004). The vegetation history during the LGM has been reconstructed by Zhao et al. (2015), who infer a distinctive vegetation biomass compared to the Holocene. This lake is thus an ideal setting to reconstruct palaeovegetation and palaeoclimatic changes during MIS3. In this paper, multi-proxies (e.g. lithology, grain size, LOI_{org}, pollen) are used to reconstruct the palaeovegetation and palaeoclimate, underpinned by a robust chronology (based on accelerator mass spectrometry (AMS) ^{14}C, optical stimulated luminescence (OSL), and palaeomagnetism). Ordination analysis of the pollen data was done to extract the primary variables correlated with the distribution of pollen samples and pollen taxa so as to infer the regional vegetation history. Our results also provide new insights into the regional response to different factors of large-scale climatic controls.