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A Tianshan Mountains loess-paleosol sequence indicates anti-phase climatic variations in arid central Asia and in East Asia

Guoqiang Li [a,*], Fahu Chen [a,b], Dunsheng Xia [a], He Yang [a], Xiaojian Zhang [c], David Madsen [a], Chris Oldknow [a], Haitao Wei [a], Zhiguo Rao [d], Mingrui Qiang [a]

[a] *Key Laboratory of Western China's Environmental Systems (Ministry of Education), College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China*

[b] *CAS Center for Excellence in Tibetan Plateau Earth Sciences of the Chinese Academy of Sciences, Beijing 100101, China*

[c] *School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing 210023, China*

[d] *College of Resources and Environmental Sciences, Hunan Normal University, Changsha 410081, China*

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A B S T R A C T

Paleoclimatic changes in arid central Asia (ACA), one of the largest arid regions in the world, are complex and the nature of these changes on orbital cycles remains unclear. Widely distributed loess records in ACA potentially provide records of paleoclimatic variation, but these records are difficult to interpret due to a lack of robust high resolution chronologies. K-feldspar pIRIR dating was employed to date 37 samples from a 13 m loess-paleosol sequence (section KS15) in an intermontane basin of the Tianshan Mountains, central ACA, NW China. The reliability of the pIRIR ages was determined by using internal checks of luminescence characteristics of the $pIR_{50}IR_{290}$ and $pIR_{200}IR_{290}$ signals, and by comparing $pIR_{50}IR_{290}$ and $pIR_{200}IR_{290}$ ages. A high resolution chronology for the loess-paleosol sequence, spanning 130–45 ka, was established using Bacon age/depth modeling. In combination with climate proxy indexes of magnetic susceptibility, total organic material, and $\delta^{13}C$ of organic remains from the sequence, our results suggest: (1) the pIRIR ages utilizing $pIR_{50}IR_{290}$ and $pIR_{200}IR_{290}$ signals are consistent for loess samples <150 ka; (2) eolian loess was deposited in intermontane basins of the Tianshan Mountains by at least $\sim$150 ka, with a steadily increasing rate of loess deposition from the last interglacial to the last glacial period; (3) ACA had a moist climate, characterized by paleosol development, during periods at 117–109, 97–85, 77–70 and 58–50 ka, corresponding to MIS 5d, MIS 5b, MIS 5–4 and MIS 3c; (4) ACA had dry climates, characterized by loess deposition, at 131–117, 109–97, 85–76, 70–58 and 50–46 ka, corresponding to MIS 5e, MIS 5c, MIS a and MIS 3b; and (5) during sub-stages of MIS 5 the ACA climate was characterized by cold-moist to warm-dry shifts which appear to be related to $\sim$21 ka precession cycles, but inversely related to Northern Hemisphere summer insolation patterns. Moisture variation in ACA thus has an anti-phase relationship to that in monsoonal East Asia. Orbital forcing may be responsible for this moisture variation in ACA.

1. Introduction

Arid central Asia (ACA) extends from Kazakhstan in the west to Mongolia in the east between approximately 35 °N and 55 °N. It is one of the driest regions in the world (Narisma et al., 2007). ACA is one of the major source areas for global atmospheric dust, which affects both the radiative forcing of climate and the production and uptake of CO_2 when the dust is deposited in the oceans after long distance transport (Prospero et al., 2002). The modern climate in ACA is dominated by the Westerlies and is arid or semi-arid, with average annual precipitation less than 400 mm (Chen et al., 2008; Zhang et al., 2016). In contrast, the East Asia summer monsoon (EASM) controls the semi-humid and humid areas of East Asia (e.g., the Central Loess Plateau (CLP) and southern China) where annual mean precipitation totals range from 400 to 2000 mm (An, 2000) (Fig. 1A and 1B). The arid environment, sparse vegetation, and fragile ecosystems make ACA highly vulnerable to climate change (Narisma et al., 2007). During historical times, large amplitude precipitation changes have resulted in shifts in lake volumes and change in the sizes of oases. These changes constitute the environmental background against which kingdoms rose and declined in these arid areas (Brooke, 2014). As a result, understanding of the

* Correspondence to: College of Earth and Environmental Sciences, Qilian Building 609A, Lanzhou University, 222 Tianshuinanlu, Lanzhou 730000, China.
E-mail address: gqli@lzu.edu.cn (G. Li).

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processes and possible mechanisms that control climatic and environmental changes in ACA on various timescales is vital for the assessment of present and future climatic and hydrological dynamics in the region and their potential effects on local populations (Chen et al., 2016; Cai et al., 2017).

ACA climate changes on suborbital and orbital timescales have been widely explored during past decades. Pollen records of lacustrine sediment from Lake Aibi in the Junggar Basin, a peat cellulose $\delta^{13}C$ record from the Chaiwobu Basin (45 km southeast of Urumqi city), and luminescence dated loess-paleosol records (e.g., LJW10 section) on the northern slope of the Tianshan Mountains indicate that Holocene effective moisture has generally increased in the central ACA during the Holocene, with the wettest conditions during the late Holocene (Wang and Feng, 2013; Hong et al., 2014; Li et al., 2015a; Chen et al., 2016). This trend is out of phase with Holocene conditions in East Asia which are characterized by: (1) a dry early Holocene, (2) a moist mid-Holocene, and (3) a relatively moist late Holocene (Chen et al., 2008; Lu et al., 2013). Climate simulation models indicate that the increasing moisture trend during the Holocene in ACA was mainly influenced by the Westerlies transporting water vapor from the Middle East which caused precipitation to increase faster than evaporation during the Holocene (Zhang et al., 2017). Locally, an Artemisia/*Chenopodiaceae* pollen record from a late Pleistocene/Holocene lacustrine sequence in the Yili Valley (Li et al., 2011), a Holocene speleothem $\delta^{18}O$ record (Cai et al., 2017), and a 500 ka speleothem $\delta^{18}O$ record from Kesang Cave in the Tianshan Mountains (Cheng et al., 2012) together provide a record of moisture change similar to a monsoon evolution model for southern China based on speleothem $\delta^{18}O$ records (e.g., Sanbao/Hulu caves, Wang et al., 2008). It has been suggested that incursions of the EASM during high insolation intervals made an important contribution to the humidity of the early and mid-Holocene, and that the moisture brought by the Westerlies was not critical to environmental changes in ACA (Mischke and Wünnemann, 2006; Li et al., 2011; Cheng et al., 2012). However, the mechanisms that control stalagmite $\delta^{18}O$ records in China are still hotly debated (Liu et al., 2015). Caley et al. (2014) used the results of a 150 000-yr transient simulation, including water isotopes, to demonstrate that Asian speleothem $\delta^{18}O$ records are not a valid proxy for EASM intensity at orbital timescales. Stalagmite $\delta^{18}O$ records are considered to be an indicator of the intensity of the Indian Summer Monsoon on orbital timescales (Liu et al., 2015), and respond to ENSO variations (a 'circulation effect') on decadal and centennial time scales (Dayem et al., 2010).

As a result of numerous conflicting records and a lack of high-resolution well-dated sequences, ACA climate changes on glacial–interglacial cycles are under debate and have hindered attempts to link patterns of climate change with neighboring areas (Cheng et al., 2012). Climatic models show that ACA climates are characterized by a warm-dry interglacial and cold-moisture glacial pattern, which differs from the warm-moist interglacial and cold-dry glacial pattern in monsoonal East Asia (Yu et al., 2003; Luo et al., 2009). A comparison of loess-paleosol records in ACA and East Asia, on the other hand, indicates that patterns of moisture change on glacial–interglacial cycles in ACA and East Asia are consistent (Ding et al., 2002). Therefore, it seems clear that the interaction between the mid-latitude Westerlies and the low latitude EASM at orbital timescales requires further investigation.

Eurasian loess provides some of the most important Quaternary terrestrial records of global scale climatic and environmental changes (Heller and Liu, 1982; Porter, 2001; Ding et al., 2002). Loess lithostratigraphy is often characterized by alternating loess and paleosol depositions, respectively reflecting intervals of relatively dry climate and relatively humid conditions (An, 2000; Porter, 2001). As a result, loess-paleosol sequences are well-suited to reconstructing moisture changes on both orbital and millennial timescales (Chen et al., 1999; Ding et al., 2002; Chen et al., 2016). However, paleoclimatic changes recorded in ACA loess-paleosol sequences are difficult to interpret due to a lack of robust chronological controls. Radiocarbon and quartz optically stimulated luminescence (OSL) dating have been employed to date loess deposits in the Tianshan Mountains area (E et al., 2012; Li et al., 2015a; Song et al., 2015). However, ^{14}C dating is limited to a maximum of 30–50 ka and reliable ^{14}C dating material is difficult to find in loess deposits (Song et al., 2015). Quartz (OSL) dating is also restricted to a maximum of ∼70–40 ka as a result of OSL signal saturation (E et al., 2012; Yang et al., 2014; Song et al., 2015; Li et al., 2016). These limits preclude the establishment of a robust long-term orbital chronology of the ACA loess record using ^{14}C dating and/or quartz OSL dating. The K-feldspar pIRIR dating method, utilizing a post IR IRSL signal with high saturation dose, can be used to date samples up to 250–300 ka (Thomsen et al., 2008; Thiel et al., 2011; Buylaert et al., 2012). This method has been successfully applied to loess-paleosol sequences in the CLP, in NE China and on the northern slope of the Tianshan Mountains (Buylaert et al., 2015; Yi et al., 2016; Li et al., 2016).

In this study, this K-feldspar pIRIR dating method was applied to 37 luminescence samples from a 13 m thick loess deposit containing multiple paleosols in the Yili Valley, Tianshan Mountains, central ACA (Fig. 1C and 1D). The reliability of the pIRIR ages was evaluated using internal checks of the luminescence characteristics of the pIRIR signals (e.g., $pIR_{50}IR_{290}$ and $pIR_{200}IR_{290}$ signals). A high resolution K-feldspar pIRIR dating chronology was then established using a Bacon age-depth model that uses Bayesian statistics to reconstruct accumulation histories for deposits. This Bayesian approach can reduce the size of age-depth model error estimates by taking into account the stratigraphic positions of the ages (Blaauw and Christen, 2011). Using this chronology, in combination with loess-paleosol lithostratigraphy and multiple proxy indexes (grain size, magnetic susceptibility [χ_{lf}], total organic carbon [TOC] and the $\delta^{13}C$ of organic matter [$\delta^{13}C_{org}$]), we reconstructed climate changes in ACA during the last interglacial to last glacial period and identified climatic patterns on orbital time scales. We then compared this record with previously published high-resolution paleoclimatic records from neighboring areas and analyzed relationships in moisture variation between ACA and East Asia. Finally, based on this analysis we use climate modeling data to identify possible mechanisms controlling paleoclimatic evolution in the region.

2. Geological setting

The Tianshan Mountains are located in central Asia and separate the Tarim Basin to the south from the Junggar Basin to the north (Fig. 1C). Loess deposits are mainly distributed in intermontane basins and on the slopes of the Tianshan Mountains (Fig. 1C). The Yili Valley is an intermontane basin in the middle of the Tianshan Mountains, and is U-shaped, with an opening toward to the west (Fig. 1C). The basin is ∼550,000 km^2, and is 350 km (east to west) by 280 km (north to south). The Yili River runs from southeast to northwest across the entire basin. Loess deposits are widely distributed on river terraces, and on piedmont and mountain slopes at elevations of 700–1500 m (Li et al., 2015b). The thickness of the loess deposits in the basin varies from a few meters to several hundred meters, with the thickest deposits (up to 200 m) in the middle of the basin (e.g., Li et al., 2015b).

The Yili Valley basin area is dominated by the Westerlies and has a typical temperate continental climate. Most precipitation occurs during spring and summer, and comes mainly from the Atlantic Ocean, and the Mediterranean, Black and Caspian seas via the Westerlies. The Siberian high dominates the regional climate