Global and Planetary Change 122 (2014) 89–106

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Time-scale and astronomical forcing of Serbian loess–paleosol sequences

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ARTICLE INFO

Article history:
Received 27 February 2014
Received in revised form 20 July 2014
Accepted 11 August 2014
Available online 19 August 2014

Keywords:
paleoclimate
Pannonian Basin
loess
astronomical time scale

ABSTRACT

The loess in Vojvodina region in Northern Serbia is regarded as one of the thickest and most complete paleoclimate archives in Europe. Recent studies showed that loess in Vojvodina spans the last million years. Based on the interprofile correlation between two most important loess–paleosol sequences Stari Slankamen and Titel Loess Plateau a synthetic profile was formed regarded as Stratotype Record of Serbian loess (SRSL). The synthetic profile has a total thickness of 62 m and is comprised of 10 loess layers intercalated with nine pedocomplexes. A new astronomically tuned age model is proposed based on correlating peak magnetic susceptibility (χ) responses with the timing of June perihelia. This target curve is derived from analysis of regional climate proxy responses during the last interglacial and independently dated last glacial–interglacial cycle of Serbian loess–paleosol sequence. The use of a precession index target as the only tuning target presents the requirement of minimal tuning approach, which means that only the precession frequencies of the record will be manipulated.

Spectral and wavelet analyses of tuned magnetic susceptibility record reveal the presence of frequencies corresponding to 139 kyr, 94 kyr, 65 kyr and small amplitude cycles of 43 and 23 kyr in χ record. Spectral analysis of frequency dependent magnetic susceptibility (χ_{fd}) has spectral content concentrated around 100 kyr and 77 kyr, while higher frequency cycles are below significance level. There is a strong 245 kyr peak in spectral results of both χ and χ_{fd} records that needs additional attention.

Around 800 kyr in SRSLχ time scale and between 900 kyr and 600 kyr in SRSLχ_{fd} series the 100 kyr cycles become dominant, which could be identified as the period of Mid-Pleistocene Transition. This is the first record of this paleoclimate transition in the Pannonian basin. The results presented in this study highlight the potential of Serbian loess–paleosol sequences for investigation of detailed and long-term climate reconstruction over continental Eurasian extent.

1. Introduction

1.1. Loess as paleoenvironmental archives

Detailed archives of Cenozoic paleoclimatic change are found in the ocean, ice and on land. Variations in oxygen isotopes measured in relatively undisturbed deep-sea sediments enable the reconstruction of the past climates going back tens of millions of years. These reconstructions allow tests of numerous hypotheses that deal with the causes of the glacial interglacial cycles, changes in their intensity and frequency, and their global impact on sea level. Ever since Hays et al. (1976) unearthed strong evidence for orbital parameters as the driver of glaciations, the presence of Milankovitch cycles has been demonstrated in deep-sea sediments in a myriad of ways.

While deep ocean sediments provide a globally integrated record, they generally do not provide specific evidence of the impact of climate change in specific regions on land. Long continuous terrestrial sequences are therefore crucial for the investigation of paleoclimatic and paleoenvironmental conditions on a scale that impacts specific ecosystems and human population. As such, terrestrial loess and lacustrine sediments have been used for the reconstruction of past climates but also for determining climate forcing mechanisms. Loess deposits comprising wind-blown dust are regarded as some of the best terrestrial equivalents of marine sedimentary records of long-term global climatic change as they are relatively continuous and undisturbed (e.g. Porter,

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http://dx.doi.org/10.1016/j.gloplacha.2014.08.007
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2001). Kukla (1970, 1975, 1977) proposed some of the first attempts to correlate paleoclimatic fluctuations recorded in loess deposits with oscillations recorded in deep-sea sediments. Since then, loess–paleosol sequences have become very important for reconstructing Pleistocene environmental processes in the terrestrial environment (e.g. Heller and Evans, 1995; Evans and Heller, 2001). The best studied long and quasi-continuous records are preserved in China, mainly on the Chinese Loess Plateau, where the deposition of aeolian sediments most likely began 22 Myr ago (Guo et al., 2002). Numerous proxies have been derived from loess and interbedded paleosols to reconstruct climatic changes, notably magnetic susceptibility (χ), grain size (GS) and geochemical indices. Variations in these proxies apparently reflect the global climatic rhythms previously revealed from marine sediments, and these were subsequently used for the development of loess depositional timescales.

1.2. Astronomical time scale

The history of geological time scale development based on the recognition of orbitally forced rhythms goes back to the 19th century. This approach was most explicitly addressed by Gilbert (1895, 1900a, b) and then further developed by Barrell (1917). However, the calculations of Milutin Milankovitch (1920, 1941) were the major turning point, although the idea that changes of orbital parameters drive 'ice ages' was not well accepted at the time (Petrović and Marković, 2012). Milankovitch's theory was subsequently proven by the findings made from the Deep Sea Drilling Project and the work of Hays et al. (1976), which ultimately led to the current paradigm of orbitally forced evolution of paleoclimate and the development of astronomically derived time scales for past environmental change. The first loess age model that was tuned to the timescale of orbital changes was introduced by Ding et al. (1994), tuning grain size variations in the Baoji loess–paleosol sequence to variations of obliquity and precession, theoretically calculated for the Pleistocene. Subsequently, many authors including Lu et al. (1999), Ding et al. (2002), Sun et al. (2006) and Han et al. (2012) have proposed timescales of Chinese loess based on the correlation of magnetic susceptibility measurements and grain size variations to orbital parameters. The main characteristic of these time scales is the application of phase free digital filters on proxy data in order to extract the frequencies, obliquity and precession which were then correlated to Earth's obliquity and precession values. Heslop et al. (2000) used a different approach consecutively to construct the time scale for the Louchuan loess–paleosol sequence. These authors did not utilize phase free digital filters on proxy variations. Instead, the chronology was formulated by directly correlating unfiltered proxy data to past changes in insolation as calculated by Laskar (1990) as well as using the orbitally tuned ODP677 $\delta^{18}O$ record as target curve (Shackleton et al., 1990).

In Europe, long, terrestrial records are scarce. Over the last decade, exposures of loess in the Middle and Lower Danube Basin have become key sites for paleoenvironmental research. Paleoenvironmental conditions over the last million years have resulted in relatively continuous deposits uninterrupted by glaciation and tundra conditions, which reflect oscillations between relatively warm-humid ("interglacial") and cold-dry ("glacial") periods. The loess deposits of the Middle and Lower Danube Basin extend to the base of the Pleistocene. The sedimentation was probably initiated in response to the formation of the Pannonian basin, retreat of the large lake systems, which once occupied it, and the increased sediment supply from the large rivers, which developed subsequently. It was during this period that hominins first arrived on the European continent, although no sites of this age have yet been discovered in the region (Fitzsimmons et al., 2012). Particularly loess sequences in the Vojvodina region of Northern Serbia, which represent long, and quasi-continuous archives of the Late and Middle Pleistocene climate evolution (e.g. Buggle et al., 2013, 2014), extend to the early Pleistocene (Marković et al., 2011, 2012b). These records developed in loess plateau sites, which is an exceptional depositional setting for European conditions, but similar to the Chinese stratotype sections. As research on the Chinese loess sequences clearly revealed an astronomical influence on climate dynamics (e.g. Ding et al., 1994, 2002; Heslop et al., 2000, 2002; Lu et al., 1999, 2004; Sun et al., 2006), similar pattern can possibly be expected in the loess record from the Middle and Lower Danube Basin.

Magnetic susceptibility measurements for Mostistea loess–paleosol section were used to develop an astronomical age model utilizing the method of Heslop et al. (2000). The authors generated time series for magnetic susceptibility using as the target curves the 65°N summer insolation (Berger and Loutre, 1991) and the stack of 57 globally distributed benthic $\delta^{18}O$ records (Lisiecki and Raymo, 2005). Spectral analysis of the obtained time series has shown the main Milankovitch periodicities (Necula and Panaiotu, 2008).

Marković et al. (2012a) were recently able to formulate the first orbitally tuned astronomical time scale for loess–paleosol sequences in the Vojvodina region. The time scale was developed using the Heslop et al. (2000) approach of correlation unfiltered magnetic susceptibility record (χ) to the insolation curve for June 65° N (Berger and Loutre, 1991) and the ODP677 $\delta^{18}O$ curve (Shackleton et al., 1990). The time scale was supplemented by paleomagnetic and aminostratigraphic techniques and provided the first detailed age model for Serbian loess–paleosol sequences. This enabled more precise correlation to other terrestrial, marine or ice core records.

The present manuscript proposes a new astronomically tuned age model based on correlating peak magnetic susceptibility values of Serbian key sites with the timing of June perihelia. This target is derived from analysis of regional climate proxy responses during the last interglacial (Tzedakis, 2005; Tzedakis et al., 2006; Stevens et al., 2011). By resolving almost every precessional cycle during the Middle and Late Pleistocene, the new age model represents an improvement of the timescale for the loess stratigraphy and paleoenvironmental evolution in the Middle Danube Basin. Spectral and wavelet analyses are used to test the presence of orbital frequencies in Serbian loess. The results from this study greatly enhance the potential of Vojvodinian loess sites for precisely reconstructing long-term climatic changes as well as climatic transitions over the Late and Middle Pleistocene in this region.

2. Materials and methods

2.1. Loess in Vojvodina: stratigraphy, key sites and the synthetic loess record

About 60% of area in the Vojvodina region is covered by loess (Fig. 1). The loess is mainly deposited on six plateaus between the rivers Danube, Tisa, Sava and Tamiš and has a maximum thickness of approximately 55 m. Numerous methods have been used to reconstruct paleoenvironmental and paleoclimatic changes (e.g. Marković et al., 2004, 2005, 2006, 2007, 2009, 2011; Fuchs et al., 2008; Buggle et al., 2008, 2013, 2014; Antoine et al., 2009; Bokhorst et al., 2009, 2011; Bokhorst and Vandenberghe, 2009; Schmidt et al., 2010; Lukić et al., 2014). Marković et al. (2008) developed a stratigraphic labeling scheme following the Chinese loess stratigraphic system (e.g. Kukla, 1987; Kukla and An, 1989), in which the loess and paleosol stratigraphic units were designated as "L" and "S" and numbered in order of increasing age. The prefix "V" is used to refer to the standard Pleistocene loess–paleosol stratigraphy of the Vojvodina (Marković et al., 2008).

For the purpose of this study the two most prominent key sites of the Vojvodina region were chosen to build a synthetic record of the Vojvodina loess: The Titel loess plateau (45°17′–18′N and 20°12′–15′E, Fig. 1), an isolated loess island, considered to have the highest accumulation rates in the region. It comprises a complete loess paleosol succession representing the last five glacial–interglacial cycles (Bokhorst et al., 2009, 2011; Bokhorst and Vandenberghe, 2009; Marković et al., 2012b).

Completeness of the last five glacial cycles of the Titel loess plateau is evaluated by the correlation of the magnetic susceptibility record to the