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Short-term soil formation events in last glacial east European loess, evidence from multi-method luminescence dating

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ABSTRACT

Here we provide a robust luminescence chronology for Stayky (Ukraine), a reference profile in European Late Pleistocene loess stratigraphy, based on optically stimulated luminescence (OSL) dating on quartz (4–11 μm, 63–90 μm) and post infrared-infrared stimulated luminescence (pIR-IRSL)) on polymineral fine grains. For the Bug loess unit, the equivalent of Marine Isotope Stage (MIS 2), results are in agreement between methods, demonstrating that the suite of embryonic soils previously interpreted as reflecting climate variability similar to Greenland interstadials (GI) actually date to ~29/27-15 ka, with most emplaced around or after 20 ka. This temporal span is further confirmed by age-depth modelling of available data. Apart from GI-2, no interstadial-type climate events are recorded in Greenland ice core data for that time interval. As short-term pedogenetic phases are also documented in records from central-western Europe, there is a need for more research into the European mid-latitude terrestrial environments response to MIS 2 hydroclimate variability.

The dating of Vytachiv paleosol, previously debatably linked to various GI events within MIS 3 resulted in ages of ~40 ± 4 ka and ~53 ± 4 ka at the lower transition, and ~26 ± 2 ka to ~30 ± 2 ka in the overlying loess. These ages indicate that the truncated Vytachiv paleosol is either not continuous, or that it encompasses a broader age range within MIS 3 than previously considered. In both cases, data would not allow for an unambiguous linking of this paleosol with specific GI events as previously attempted.

The pIR-IRSL$_{290}$ dating of the loams immediately underneath Pryluky unit in the range of ~120 ka to ~168 ka and of the Pryluky mollisol from ~90 ka to 126 ka confirm the broad correspondence of this unit with MIS 5, although poor dose recovery results open the possibility for further testing on the degree these ages provide overestimated results. Quartz data severely underestimate the pIR-IRSL$_{290}$ ages for these samples. The application of pIR-IRSL$_{290}$ dating for the underlying Dnieper till previously linked to the Saalian glaciation resulted in natural signals at the level of laboratory saturation, yielding minimum ages of c. 700 ka. For the same sample, the natural SAR-OSL signals for 4–11 μm quartz were found significantly below laboratory saturation level, resulting in finite ages of ~250–270 ka interpreted here as underestimates, while coarse quartz (63–90 μm) signals reached about 85% of the laboratory saturation level. These data suggest extreme caution must be taken when dating such old samples using quartz OSL. Results from our high-resolution luminescence dating raises important implications for the chronological representativeness of Stayky as a key loess site in Eastern Europe beyond MIS 2.

1. Introduction

Loess-paleosol sequences (LPS), as some of the most spatially spread terrestrial deposits, provide crucial insights into past

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environmental dynamics, particularly where other long-term paleoclimate data are scarce (Kukla, 1977; Heller and Liu, 1982; Vandenberghe, 2000; Panaiotu et al., 2001; Guo et al., 2002; Lindner et al., 2006; Buggle et al., 2008, 2013; Haesaerts et al., 2010; Kusiak et al., 2012; Jary and Ciszek, 2013; Obreht et al., 2016; Zeeden et al., 2016; Gozhik et al., 2014; Marković et al., 2011, 2015). Owing to the nature of their formation (Sprafke and Obreht, 2016), the LPS are valuable in investigating past variability in atmospheric particle loading (Ruth et al., 2007; Bokhorst et al., 2011; Rousseau et al., 2017a; b) and long-term global dust dynamics (Kohfeld, 2003; Delmonte et al., 2004; Újvári et al., 2016a). As the primary constituent of loess, mineral dust is a major component of global climate forcing (Maher et al., 2010; Sima et al., 2013; Újvári et al., 2016a; Longman et al., 2017) and a proxy that has allowed for direct comparison of LPS with chronologically better resolved ice and marine records (Evans et al., 2003; Svensson et al., 2008; Veres et al., 2013a; Rasmussen et al., 2014; Rousseau et al., 2007, 2011; 2017a; b; Moine et al., 2017).

Investigations of Eurasian LPS document a pattern with mainly, if not only well-developed major paleosols interbedded with thick loess horizons (Ding et al., 2002; Guo et al., 2002; Hao et al., 2012; Buggle et al., 2008, 2013; Marković et al., 2011, 2015; Fitzsimmons et al., 2012; Zech et al., 2013; Zeeden et al., 2016). These records have been linked to orbital forcing driving glacial-interglacial cycles (cf., Heller and Liu, 1982; Lisiecki and Raymo, 2005; Lang and Wolff, 2011), with major paleosols formed during interglacials and loess horizons representing stadial conditions with enhanced global dust cycling (Marković et al., 2015 and references therein).

Overall, reliable chronological control is still the major limiting factor in exploring the full paleoclimate potential of LPS (Vandenberghe, 2000; Hao et al., 2012; Basarin et al., 2014; Marković et al., 2011, 2015; Obreht et al., 2016; Zeeden et al., 2018a; b). Moreover, mainly along mid-latitudes in Eurasia or along major river valleys, incipient (or embryonic) soils have been described within the last glacial loess or loess-derivates (Vandenberghe et al., 1998; Haesaerts and Mestdagh, 2000; Antoine et al., 2001, 2013; Gerasimenko, 2006; Haesaerts et al., 2010, 2016; Rousseau et al., 2001, 2011; Bokhorst et al., 2011; Fuchs et al., 2013; Jary and Ciszek, 2013; Meszner et al., 2013; Terhorst et al., 2014; Lehmkuhl et al., 2016). Such short-term phases of pedogenesis have been regarded as likely equivalents of Greenland interstadials (GI) (Rousseau et al., 2011, 2017a; b; Moine et al., 2017) and linked to rapid changes in moisture availability (Antoine et al., 2001; Gerasimenko, 2006; Rousseau et al., 2011). As millennial-scale climate variability is well expressed in paleoclimate records from within the European loess belt as periods of enhanced/diminished organic productivity and biomass development (Caspers and Freund, 2001; Ampel et al., 2008; Wohlfarth et al., 2008; Fleitmann et al., 2009; Veres et al., 2009; Sanchez Goñi and Harrison, 2010; Fletcher et al., 2010; Shumilovskikh et al., 2014; Magyari et al., 2014; Sirocko et al., 2016), it is reasonable to assume that even short-term enhanced ground moisture sustaining biomass growth should be reflected in loess records as well. On the contrary, the typical loess plateaus of southeastern Europe were regarded as too dry for sustaining short-term phases of pedogenesis (Buggle et al., 2013; Marković et al., 2015); recent works proved however that MIS 3 millennial-scale climate variability is discernible in moisture and weathering proxies (Hatté et al., 2013; Obreht et al., 2017; Zeeden et al., 2018).

Major questions that require further research concern the temporal and spatial development of such embryonic soils (Labaz et al., 2018) and their regional representation in pedostratigraphic terms (Bábek et al., 2011; Gocke et al., 2014; Łanczont et al., 2014). Lateral changes in geological and geomorphological characteristics (Stevens et al., 2011; Antoine et al., 2013; Kadereit et al., 2013; Meszner et al., 2013; Terhorst et al., 2014; Vandenberghe et al., 1998, 2014; Lehmkuhl et al., 2016; Fischer et al., 2018), or local to regional periodic shifts in hydroclimate conditions (Bokhorst et al., 2011; Buggle et al., 2013; Hatté et al., 2013; Sima et al., 2013; Zech et al., 2013; Hošek et al., 2015; Obreht et al., 2016, 2017) further complicate the validity of regional pedostratigraphic relationships (see Marković et al., 2015 and references therein). This includes the correlation of paleoclimate events among LPS records and with other paleoclimate archives (Evans et al., 2003; Shi et al., 2003; Maher et al., 2010; Újvári et al., 2016b; Fitzsimmons et al., 2012; Basarin et al., 2014; Zeeden et al., 2018a; Kadereit and Wagner, 2014; Govin et al., 2015; Rousseau et al., 2007, 2017a; b; Sauer et al., 2016; Moine et al., 2017). These issue are even more compelling when considering the role LPS might play in disentangling regional or even hemispheric past climate scenarios if considered within a larger and widely applicable chronostratigraphic framework (Sima et al., 2013; Govin et al., 2015; Moine et al., 2017; Obreht et al., 2017; Rousseau et al., 2017a; b).

In northern Ukraine at Stayky LPS (Fig. 1a–b) a record of past rapid climate variability expressed as the alternation of loess beds and several thin, incipient or embryonic soils has been documented within the Bug loess unit (Fig. 1c–d) (Gerasimenko, 2006; Gerasimenko and Rousseau, 2008; Rousseau et al., 2011). On these grounds, Stayky is considered an important record for exploring environmental dynamics during the last glacial period in eastern Europe (Rousseau et al., 2011, 2017a; b; Sima et al., 2013; Moine et al., 2017). However, because of insufficient dating (Rousseau et al., 2011), the proposed chronological setting and correlation of embryonic soils with Greenland Interstadial (GI) events has been questioned by Kadereit and Wagner (2014).

To date, luminescence techniques remain the main methods in providing radiometric data for loess following their applicability in directly dating the emplacement time of mineral particles (Roberts, 2008). In recent years, chronological and methodological advances have been achieved in the luminescence dating of eastern European LPS (Balescu et al., 2003; Stevens et al., 2011; Timar et al., 2010; Vasiliniuc et al., 2012, 2013; Constantin et al., 2014). This includes comparisons of luminescence with tephrochronology or radiocarbon dating (Constantin et al., 2012; Fitzsimmons et al., 2013; Veres et al., 2013b; Anechitei-Deacu et al., 2014; Gozhik et al., 2014; Trandafir et al., 2015; Újvári et al., 2016b) and correlative age models (Obreht et al., 2017; Zeeden et al., 2018). However, issues linked to the grain size dependency of saturation characteristics and uncertainties induced by varying water contents (Timar-Gabor et al., 2011, 2012; 2015, 2017; Timar-Gabor and Wintle, 2013) still limit the application of luminescence data in age-depth modelling (Blaauw et al., 2010; Stevens et al., 2011; Újvári et al., 2016b; Zeeden et al., 2018b), precluding a secure identification of past climate events in loess records.

In order to substantiate the chronology of Stayky LPS, results of multi-method luminescence investigations of fifteen samples (Fig. 1d–e) are reported. State of the art optically stimulated luminescence (OSL) dating has been applied on all samples, alongside post infrared-infrared stimulated luminescence (pIR-IRSL) dating. Each sample has been dated using different grain-sizes and water content assessments; the results allow for a more comprehensive chronological overview of the Stayky sequence than previously achieved.

2. Regional chronostratigraphic considerations and issues

In the Ukrainian Quaternary chronostratigraphic framework (Veklitch, 1993), six units were established above the Dnieper (Saalian) glaciogenic deposits. Two correlation schemes with MIS stages are in use. In the first, the Dnieper (dn) unit is the equivalent