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Characterisation and palaeoclimate of a loess-like permafrost palaeosol sequence in NE Siberia

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Abstract

We studied a 15 m high loess-like permafrost palaeosol sequence (the Tumara Palaeosol Sequence, TPS), which developed on a Middle Pleistocene fluvio-glacial terrace of the Tumara River. Various analytical methods were applied to characterise the TPS. Similar to typical loess–palaeosol sequences (e.g. in China, Europe etc.), pedogenetic clay formation, mineral weathering and smaller grain sizes are interpreted as representing warmer and more favourable climatic conditions (interglacials or interstadials). Soil organic matter (SOM), however, reveals an unfamiliar, inverse pattern: High organic carbon contents ($C_{org} > 1\%$) characterise the dark grey glacial palaeosols, whereas lower contents ($C_{org} \leq 0.5\%$) are found in the brown interglacial/-stadial palaeosols. This can be explained with permafrost and water logging having inhibited SOM mineralisation during cold periods. D/L ratios of aspartic acid and lysine proved to be useful proxies for both SOM aging and palaeotemperature with amino acid racemization being enhanced in interglacial/-stadial palaeosols. On the basis of the geochemical and grain size results, further palaeoclimatically relevant proxies describing the palaoewind-strength (U-ratio), the mineral weathering (Chemical Index of Alteration, Rb/K) and the changing mineral input signal (Ba, Ti/Zr, Ti/Al) were applied to the TPS. In combination with numeric dating results (radiocarbon and luminescence) and in the context of other northern hemispheric records, the simple warm-cold stratigraphy as derived from the palaeoenvironment/-climate proxies suggests that the TPS represents the last ~240,000 years.

Keywords: Quaternary; NE Siberia; Loess-like palaeosol sequence; Geochemistry; Grain size; Magnetic susceptibility; Amino acid enantiomers

1. Introduction

Loess and loess-like sediments are valuable archives for the reconstruction of the palaeoenvironment and the palaeoclimate. Not only can loess–palaeosol sequences be considered as terrestrial counterparts to marine and ice core records (e.g. Imbrie et al., 1984; Martinson et al., 1987; Johnsen et al., 2001), they also improve our understanding of how various ecosystems responded to climate changes in the past. So far, northern hemisphere eolian records have attracted much attention in Europe, Central Siberia, China, Alaska and Midcontinental North America (e.g. Heller and Liu, 1982; Kukla, 1987; Chlachula et al., 1997; Frechen and Dodonov, 1998; Muhs and Bettis, 2000; Berger, 2003; Zöller et al., 2004). A continuous, long-term archive has however not yet been described for NE Siberia, a key region between Greenland and Lake Baikal, Eastern Siberia. There, ice cores (e.g. Dansgaard et al., 1993; Johnsen et al., 2001) and lacustrine sediments (e.g. Karabanov et al., 1998; Prokopenko et al., 2001; Swann et al., 2005), respectively, have been studied intensively and at high resolution during the last decades.

In this paper, we present and discuss results obtained for the Tumara Palaeosol Sequence (TPS), NE Siberia (Fig. 1), in order

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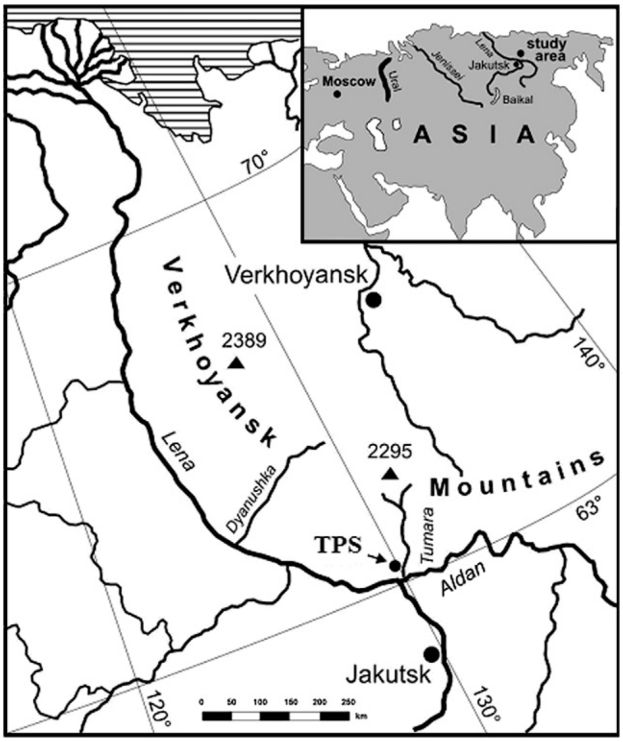

Fig. 1. Map showing the location of the study area in Northeast Siberia. The "Tumara Palaeosol Sequence" (TPS) is situated at the right (west) bank of the Tumara River and exposes 15 m of loess-like palaeosols preserved in permafrost.

to evaluate the potential of these loess-like sediments to contribute to the reconstruction of the Quaternary environmental and climatic history of the study area. We specifically address:

- Grain size distribution: Nugteren and Vandenberghe (2004) and Porter and An (1995), for instance, have shown that grain size in Chinese loess correlates with wind strength. Coarser sediments document intensified winds entraining larger particles and are therefore often correlated with unstable glacial periods or cold events during glacial–interglacial cycles. On the other hand, clay formation in loess–palaeosol sequences is increased due to enhanced weathering/pedogenesis during warmer and more humid climatic conditions (interglacials/-stadials).
- Geochemical composition: The geochemistry of loess from different regions can be highly variable, reflecting diverse dust sources (Gallet et al., 1998). Moreover, selective removal of elements during weathering and pedogenesis changes the original input signal and thus allows estimating weathering intensity (Gallet et al., 1996; Ding et al., 2001; Yang et al., 2004). Elemental indices or their ratios (e.g. K/Na, K/Ca, Ca/Sr or Ti/Zr) have been established and used successfully to assess changes in provenance and weathering.
- Magnetic susceptibility (MS): MS may provide a tool for dating by correlation with other profiles and marine records. In Chinese loess–palaeosol sequences this approach is widely and successfully applied (e.g. Heller and Liu, 1982; Heslop et al., 2000; Kohfeld and Harrison, 2003). The concept of magnetic dating there is based on the biotic and abiotic formation and accumulation of ultrafine-grained magnetite during interglacial/-stadial periods coinciding with increased precipitation and enhanced soil formation (Xiuming et al., 1993; Liu et al., 1995; An, 2000; Evans and Heller, 2001; Sartori et al., 2005). On the contrary, in Central Siberia and Alaska higher MS values have been found in glacial loess deposits compared to the interglacial/-stadial soils (Begét, 2001; Chlachula, 2003; Evans et al., 2003). This inverted signature has been attributed to the ability of stronger winds to entrain and transport dense iron oxide particles ('wind vigor model').
- Soil organic matter (SOM): Interglacial and interstadial palaeosols typically have higher SOM contents than the intercalating loess sediments (e.g. Muhs et al., 2003b). On the one hand, this is generally attributed to higher organic matter production during warm periods and/or rapid loess accumulation during glacials/stadials (shown for instance by Zander et al. (2003) for the Central Siberian Kurtak Loess record). On the other hand, inhibition of SOM mineralisation (and thus SOM accumulation) due to permafrost and water logging might be worth a more detailed consideration especially in boreal and arctic regions, like e.g. NE Siberia. According to our knowledge, only few palaeosol sequences show an "inverse" SOM pattern with higher organic matter contents correlating with glacial periods and lower ones characterising interglacial palaeosols (e.g. Zech, 2006). Apart from the standard SOM parameters C_{org}, N and C_{org}/N, we will also present amino acid enantiomers as biomarkers. Amino acids, mainly bound in proteins, constitute an important N-pool in soils (Amelung, 2003). Containing a chiral C-atom, they can occur either in the left-handed form (L-enantiomer) or in the right-handed form (D-enantiomer) with living organisms primarily producing the L-enantiomers. The D-amino acids are then generated by racemization – a mainly time-, temperature- and pH-dependent abiotic reaction – from their respective L-enantiomers (Bada, 1985). It has therefore been suggested that D/L ratios of amino acids can be used for dating. Mahaney and Rutter (1989), for instance, found the ratio D/L-aspartic acid to be a suitable geochronometer in buried soils.

Overall, it should be emphasized that the TPS is not a typical loess sequence, but rather a loess-like palaeosol sequence. The eolian material in all parts of the profile was respectively subjected to pedogenetic processes, and possibly re-worked. Nevertheless, the analytical results suggest that the TPS is built up of alternating glacial and interglacial/-stadial palaeosols. On the basis of this simple "cold-warm" stratigraphy, the combination with numeric dating results, and the comparison with other northern hemispheric records, we here propose a tentative chronology for the TPS.

2. Geological setting and stratigraphy of the Tumara palaeosol sequence

The Verkhoyansk Mountains are located in Northeast Siberia and are characterised by boreal continental climate, i.e. short,