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Late Pleistocene dust dynamics and pedogenesis in Southern Eurasia – Detailed insights from the loess profile Toshan (NE Iran)

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A B S T R A C T

In southern Eurasia recurrent phases of aridization, dust source extension and enhanced Aeolian sedimentation alternated with moister intervals, promoting reduced deflation areas and dust accumulation in the context of late Pleistocene climate changes. Weathering and soil forming intensity in this greater region are, hence, mainly governed by fluctuations in the balance between dust supply and moisture availability.

Among the hitherto known sections, the Toshan loess-soil sequence (LPS) represents a key site due to the quality of the record and the multitude of available data giving detailed insights into the timing and magnitude of dust accumulation and soil formation of the region. To elucidate these dynamics for much of the past 130.000 years bulk mineralogical and geochemical data are presented supplemented by a high resolution magnetic susceptibility record and by the results of a detailed micromorphological study of loess at Toshan.

The last interglacial Luvisol/Phaeozem-like (~MIS 5e) and the early glacial interstadial steppic palaeosols (~MIS 5 c and a) are characterized by gradually increasing grain-size and decreasing degrees in decomposition of micaceous and mafic minerals. Pronounced feldspar weathering is detected in the last interglacial and modern soils only, which formed under reduced or absent dust deposition on penultimate and last glacial loess, respectively (postsedimentary). The overall pedosedimentary conditions correspond to large scale trends of increasing drought, dust accumulation and wind strength in southern Eurasia in relation to decreasing moisture availability towards the early Pleniglacial (~MIS 4), causing soil formation under ongoing dust deposition (synsedimentary). Similar intervals of synsedimentary soil formation are recorded during the interglacial/interstadial-stadial transitions of the early glacial and during pleniglacial (~MIS 4 to 2) interstadials. The latter are marked by gradual increases in magnetic susceptibility, colour and decreasing texture. Conversely, silicate weathering could not be detected, suggesting that grain-size fluctuations are a primary feature. Thus, windy and arid pleniglacial conditions in southern Eurasia were interrupted by intermittent phases of synsedimentary soil formation, in response to short-lived and relatively moist interstadials. Although the interrelation of these incipient soils, throughout southern Eurasia is afflicted with considerable restrictions, the oscillatory pattern of the Toshan LPS bears great similarity with millennial-scale oscillations recorded in limnic archives of western Asia.

1. Introduction

Loess belongs to the most widespread terrestrial archives of Quaternary climate change, as it covers ca. 10% of the global land

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surface (Muhs and Budahn, 2006). Within the Eurasian loess belt most scientific attention was attributed to the loess successions of southeastern Europe (e.g. Antoine et al., 2001; Buggle et al., 2009; Obreht et al., 2014; Marković et al., 2015; Zeeden et al., 2017) and Central Asia (e.g. Dodonov, 1991; Dodonov and Baiguzina, 1995; Mestdagh et al., 1999; Machalett et al., 2006, 2008; Dodonov et al., 2006; Fitzsimmons et al., 2016). Thus, considerable knowledge gaps remain to be closed in western Asia and the Caspian Sea region in particular as a transitional area between these greater regions.

Loess-palaeosol sequences (LPS) often provide the most widespread terrestrial records suited for the characterization and reconstruction of past climatic fluctuations over wide areas (Muhs and Budahn 2006; Marković et al., 2015).

Climate change in LPS is recorded by the degree of loess weathering, resulting in the formation of palaeosols (Ujvári et al., 2008; Bokhorst et al., 2009; Buggle et al., 2011; Zeeden et al., 2017). In most areas of the Eurasian loess belt dust accumulation and conversion to loess have occurred during cold and arid stadials, while palaeosols have formed under more favourable climatic conditions during interglacials and interstadials. More humid conditions promote hydrolysis and protolysis and thus decalcification, minerals weathering and soil formation (Smykatz-Kloss, 2003; Buggle et al., 2011). Moreover, secondary minerals may form such as superparamagnetic iron oxides, pedogenic iron (hydr) oxides, clay minerals and carbonates affecting not only the rock magnetic properties of a weathering profile, but also its granulometric and colorimetric properties, respectively (Vandenberghe et al., 1985; Cornell and Schwertmann, 2003; Evans and Heller, 2003; Kehl, 2010; Rolf et al., 2014; Buggle et al., 2014; Vlaminck et al., 2016). Processes of weathering are related to plant growth and activity of microorganisms and animals living on past land surfaces or within near surface loess layers. Overall, the intensity of weathering and pedogenic alteration of loess may be considered basically a function of palaeoprecipitation (Bokhorst et al., 2009; Buggle et al., 2014), while palaeotemperature as a control on all physico-chemical process rates also plays a role.

Accumulation of calcareous dust and pedogenesis represent two competing processes (Guo et al., 1996; Kemp, 2001) and depending on dust accumulation rates and climatic conditions at past land surfaces, the degree of weathering and pedogenic alteration of loess has varied in time. Subtle or gradual changes in loess properties may well reflect climate driven differences in the degree of bioturbation, accumulation of organic matter or partial carbonate leaching. Besides applying a static genetic approach of post-sedimentary pedogenesis on stadial loess, synsedimentary pedogenesis has to be taken into account to fully reflect the late Pleistocene dust and soil formation dynamics, as suggested earlier for NE-Iranian loess (Vlaminck et al., 2016).

Palaeoclimate research by means of LPS in central Asia basically focused on the dynamics of interglacials and glacials within the Brunhes-Matuyama chron or even beyond, operating on astronomical timescales (e.g. Dodonov, 1991; Dodonov and Baiguzina, 1995; Dodonov et al., 2006). Recently, more focused approaches were applied concentrating on dust and soil formation dynamics during the last interglacial-glacial cycle (Mestdagh et al., 1999; Machalett et al., 2006, 2008) or during parts of the last pleniglacial, which is defined as the period from ~74 ka to ~13 ka, thus encompassing marine isotope stages (MIS) 4, 3 and 2 (Huijzer and Vandenberghe, 1998; Feng et al., 2011; Fitzsimmons et al., 2016). Conversely, in western Asia pollen records from Lake Van provide evidence of long-termed and short-lived vegetation changes during the late Pleistocene (Litt et al., 2014; Pickarski et al., 2015), while climate driven fluctuations in dust accumulation and soil formation during the last interglacial-glacial cycle are not sufficiently known.

In northern Iran, loess occurs on the northern declivity of the Alborz Mountains and in the so-called Iranian Loess Plateau (ILP; Fig. 1). There, westerly cyclones, the Siberian anticyclone, subtropical and polar air masses and local front systems constitute a complex synoptic climate pattern, promoting dust storms as well as a steep hydroclimatic gradient (Alijani and Harman, 1985; Orlovsky et al., 2005). It is, therefore, likely that dust deposition and precipitation have reacted sensitively to long and short-termed climate fluctuations as suggested by recent studies at different locations (Kehl et al., 2005; Frechen et al., 2009; Kehl 2010, Vlaminck et al., 2016; Ghafarpour et al., 2016; Wang et al., 2016, 2017; Lauer et al., 2017a, 2017b; Taheri et al., 2017). Highly-resolved analyses of northeastern Iranian LPS, therefore, bear great potential to improve the palaeoclimatic record at the interface of western Asian pollen records and central Asian loess deposits.

The Toshan LPS stands out from other NE Iranian LPS by its highly detailed stratigraphy and exceptional amount of available data (Vlaminck et al., 2016; Lauer et al., 2017a, 2017b). The Toshan site includes 26 m of loess in which at least nine palaeosols are intercalated showing differential degrees of soil development. Thus, the Toshan section gives an excellent opportunity to thoroughly characterize and determine different degrees of weathering and soil formation in loess throughout the late Pleistocene of NE Iran.

In order to do so we determined geochemical weathering indices relying on the depletion of soluble mobile elements and the enrichment of less soluble and immobile elements, which are thought to be hosted by the same carrier mineral (Buggle et al., 2011). Additionally, we established the first high resolution record of mass specific and frequency dependent magnetic susceptibility of NE Iranian loess, because the parameters are known to be sensitive for detecting even weak pedogenic alterations (Heller and Liu, 1982; Dearing et al., 1996; Maher, 1998). We supplemented these analyses by mineralogical evidence and conducted a detailed micromorphological investigation in order to demonstrate differences in soil structure, degree of carbonate leaching and accumulation of secondary carbonates, as well as expression of pedogenic features, indicative of the type and intensity of past soil formation processes. In the present paper, these results are aggregated with previous high-resolution records on grain-size and colour (Vlaminck et al., 2016) and discussed before the background of dust accumulation vs. soil formation dynamics of the last interglacial-glacial cycle of NE Iran. Our palaeoclimatic and palaeoenvironmental conclusions are placed into a supraregional context by comparison with eastern and central Asian limnic and loess records.

2. Study area and previous investigations of LPS at Toshan

In northern Iran loess is found along the northern foothills of the Alborz Mountains and (Fig. 1) in the westernmost part of the Kopet Dagh Mountains. In both mountain ranges loess is unconformably overlying the respective bedrock. Along the Alborz Mountains the bedrock is mainly composed of Jurassic limestone and metamorphic rocks such as the Gorgan schists, whilst in the ILP the bedrock largely consists of Cretaceous shales and limestones.

These loess-soil sequences are located along a modern precipitation gradient spanning the range from subhumid conditions in the West near the loess section at Neka to semiarid conditions towards the North and North-east at the loess section at Agh Band. Modern soils of the area represent a climosequence with differential degrees of soil formation, expressed by their respective morphology, clay mineralogy and their physicochemical properties corresponding to decreasing humidity from West to East (Khormali and Kehl, 2011). The majority of precipitation is associated with the