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Sensitivity of frost weathering and aeolian deposition during genesis of Late Quaternary periglacial slope covers on calcareous rocks of a Muschelkalk landscape, eastern Thuringian Basin, Germany

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ABSTRACT

Pleistocene, periglacial loose rock covers on calcareous rocks of Mesozoic Muschelkalk contain sediments, which are derived from loess deposition, frost weathering as well as limestone dissolution processes. Distinct sediments form periglacial slope deposits (PSD) with a layered vertical structure, consisting of Basal Layers (BL), Intermediate Layers (IL) and Upper Layer (UL). The Basal Layer has in part a notably more complex structure than on siliceous or quartz bedrock. The lithological and petrological properties of calcareous rock types are reflected by remarkably different structure, thickness and clast properties of frost shattered debris within the investigated Muschelkalk landscape as well as in chemical weathering rates within the debris. Furthermore, we could detect a high variability in the thickness and distribution of aeolian matter, too. We assume that the deposition of loess sediments might be sensitive to both properties and patterns of debris cover and to the amount of pre-existing "Braunlehm" that resulted from limestone dissolution processes. Soil moisture conditions and vegetation cover might have been as crucial factors for loess distribution as luff-/lee-effects of the regional wind system or karst surface morphology. Considering the ecological consequences implied by the structure and heterogeneity of periglacial loose rock cover, limestone landscapes in general seem to be vulnerable to degradation processes. Particularly sites of shallow sediment depth or rich in rock debris might be rapidly degraded by soil erosion, have low protection potential against groundwater pollution and might have a high sensitivity towards climatic impacts like water shortage and drought stress.

1. Introduction

1.1. Periglacial processes and periglacial slope deposits (PSD)

During the Last Glacial Maximum (LGM) widely spread loose rock covers developed over solid bedrocks under periglacial conditions in large areas of Middle Europe. The material of loose rock covers is contributed by frost weathering of bedrock, i.e. the disintegration of rock and the disposal of rock debris, and by deposition of allochthonous aeolian fines. These substrates are translocated, altered and partly mixed by gelifluction, cryoturbation as well as wash-off processes, thereby forming a layered, mostly bi- or three-parted vertical structure.

Classifications of periglacial slope deposits (PSD) date back to the 1960th (Schilling and Wiefel, 1962; Semmel, 1968) and have been adapted for other landscapes and applied to more practical questions, e.g. nutrient supplement or landscape water regime, by several authors (e.g. Altermann et al., 1988; Kleber and Schellenberger, 1998; Lorz and Phillips, 2006; Semmel, 1994; Stahr, 1979; Völkel, 1993). Today, the German Soil Mapping Manual (AG Boden, 2005) gives an established, official classification system for PSD, which are separated in: Upper Layer (UL), Intermediate Layer(s) (IL), Basal Layer(s) (BL). The terms "Upper Layer", "Intermediate Layer" and "Basal Layer" used in the present paper refer to the translation by Kleber (1992) and are synonymous to the German terms "Hauptlage", "Mittellage" and "Basislage" as defined in the German Soil Mapping Manual (AG Boden, 2005).

Rock debris, derived from frost weathering processes, relocated by gelifluction on slopes or altered by cryoturbation on plains, is defined as *Basal Layer (BL)*. Basal Layers are widespread in nearly all relief positions. They show varying thicknesses and even multi-layered structures. Basal Layers generally do not contain aeolian matter or just in very little amounts. In contrast, aeolian material is an important constituent of the Intermediate Layer and the Upper Layer, but it can become less important in some cases (e.g. Völkel, 1993). The loess-rich *Intermediate Layer (IL)* generally contains rock fragments of the Basal Layer, which were admixed by gelifluction. In present distribution, Intermediate Layers are preserved in relief positions, which were either well protected against periglacial erosion or especially prone to loess accumulation (e.g. Sauer and Felix-Henningsen, 2006; Völkel et al.,

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2002). Besides loess and rock fragments, the *Upper Layer (UL)* may contain typical volcanic minerals of Laacher-See-volcanism (Semmel, 1968, also Terhorst, 2007). The volcanic ashes were admixed into the Upper Layer by gelifluction during its genesis in the Younger Dryas (e.g. Semmel and Terhorst, 2010). The Upper Layer is ubiquitous in nearly all relief positions with a remarkable steady thickness of 50 cm +/− 20 cm (Semmel, 1968), which have been claimed to be the former depth of an active layer (Kleber, 1992; Scholten, 2003); an assumption that is still under discussion, since the existence of widespread permafrost during the Younger Dryas is called in question (e.g. Semmel, 1998). Holocene anthropogenic land use and forming of anthropogenic solum sediments may have reduced the thickness of the Upper Layer or may even have removed it completely.

1.2. Periglacial slope covers on calcareous rocks

Periglacial slope covers on calcareous rocks of Mesozoic Muschelkalk have been described in previous studies as markedly rich in rock debris and poor in fine matter. The loose rock cover is often thin or even absent (e.g. Hempel, 1955; Rohdenburg and Meyer, 1963; Semmel, 1968; Steinmüller, 1996). Furthermore, an ascertained high variability of loose rock cover, including a high variability of aeolian sediments, implies a high variation in soil forming and soil properties (Thöle and Meyer, 1979).

These general features make calcareous landscapes principally vulnerable to degradation processes and anthropogenic impacts.

i) Less intensive land use and minor soil erosion processes might already lead to heavy degradation as loose rock covers and soils are generally thin. For this reason profiles on limestone are assumed to be indeed in part degraded by soil erosion processes (Semmel, 1968; Terhorst, 1997). ii) Groundwater protection in limestone landscapes, particularly in karstic landscapes, highly depends on the overlying sediment covers, which represent the single drainage filter. If the sediment cover is solely built up by PSD, than their structure, thickness or state of degradation determines the protection potential against pollutant or nitrate seepage (Semmel, 1994; Zielhofer, 2009). iii) Sites of very shallow sediment depths and rich in rock debris might be highly sensitive towards climatic impacts, as they are particularly prone to e.g. water shortage and drought stress.

For these reasons, information about genesis, properties and distribution of loose rock covers in limestone landscapes are necessary and furthermore, information about how these attributes of periglacial slope deposits are linked to relief and bedrock properties. This would help to explain the variability of loose rock and soil cover development, and might allow an estimation of the actual state of landscape and soil degradation.

Thus, (1) the linkage of frost weathering of bedrock and bedrock properties is investigated. Sedimentary rocks of the Muschelkalk mainly consist of calcareous rocks, which are yet different in their amount of insoluble residues as well as in their lithogenic properties (e.g. bedding spacing, muddy interbeddings) (see Table 1). Besides moisture conditions and character of freeze–thaw-cycles, bedrock properties (strength, jointing and porosity) and the degree of water saturation of rock (e.g. Dredge, 1992; Prick, 1997) determine the kind of frost weathering processes (Matsuoka and Murton, 2008) and therefore the rate of debris production as well as shape and size of the resulting rock fragments. Generally, it is assumed that ice segregation, as one kind of rock disintegration (Matsuoka, 2001), occurs in moist, porous rocks where liquid water migrates along a temperature gradient to freezing points (Matsuoka and Murton, 2008). Solid, jointed rocks of low porosity are mainly prone to volumetric expansion of ice within joints that generates or widens cracks and leads to larger rock fragments (*"macrogelivation"*, cf. Matsuoka, 2001).

For these reasons, features of frost weathered debris might be attributed to certain properties of the different calcareous rocks of Muschelkalk.

(2) Residues of limestone dissolution are incorporated in periglacial slope deposits in limestone landscapes (Altermann and Rabitzsch, 1976; Kleber, 1991; Pawelec, 2006; Terhorst, 2007). These insoluble, siliceous limestone components are clayey–loamy and, in the Mid-latitudes, predominantly tinted brown, yellowish or reddish brown. In the present paper, the term "Braunlehm" is used for such brown tinted, clayey–loamy sediments that can be ascribed to residues of limestone dissolution. They may cover the solid or loosened bedrock in-situ, but being relocated in most cases. "Braunlehm" is often mixed with other sediments like limestone debris or aeolian fines, what is also reflected in the results of the present study; and emphasises their (repeated) translocation (e.g. Pfeffer, 2004; Schlichting, 1993). The amount of "Braunlehm", produced during a certain period of time strongly depends on limestone properties (e.g. amount of insoluble residues, porosity and fossil content) that influence the specific dissolution tendency of the rock (Scheffer et al., 1962). Furthermore, the grade of rock disintegration and rock debris size also determine the rate of dissolution. Thus, the amount and distribution of clayey–loamy "Braunlehm" might also be traced back to specific limestone properties. Additions of "Braunlehm" may alter the properties of basal rock debris (Basal Layer) and of periglacial slope deposits at the whole.

(3) Remarkable differences in thickness and distribution of aeolian matters can be recognised on the local scale in limestone landscapes (e.g. Bullmann, 2010; Thöle and Meyer, 1979). The drift and deposition of aeolian matters affected the Mid-latitude submountainous areas of Germany during cold and dry climatic periods of the Late Pleistocene (Middle/Upper Pleniglacial, cf. Sauer, 2004). Their regional distribution is affected by altitude as well as luff-/lee-effects. Nevertheless, there might be evidences, that the distribution of aeolian fines is controlled by further factors on the local scale.

2. Material and methods

2.1. Study area

The study area is located between 300 and 470 m above sea level (a.s.l.) at the Ilm–Saale–Muschelkalk-plateau which is located at the eastern frame of the Thuringian Basin (Fig. 1). Sedimentary rocks of Muschelkalk (Middle Triassic) of marine origin are mainly composed of calcareous rocks with high carbonate contents (75–>96%). Fine-bedded limestone facies have a horizontal to undulose stratification with marl, muddy or crystalline interbeddings. Heavy-bedded limestone generally has wide-standing joints and shows a bioclastic, partly porous character. Marl or clayey layers as well as saline and sulphurous sediment sections are partly interbedded (Table 1). Based on their lithogenic and petrologic properties the calcareous rocks show a differentiated resistance due to both physical (fracture) and chemical weathering processes ("specific dissolution velocity" cf. Scheffer et al., 1962).

The study area is only slightly affected by the dry climate of the inner, lower lying basin (150–200 m a.s.l.) which is located leeward from the Harz Mountains. Precipitation rises with increasing elevation and has an annual average of 600–700 mm in the study area (Schramm and Hanußek-Biermann, 1995). The mean annual temperature is 7.5 °C. While the inner Keuper basin is widely covered by Weichselian loess, the loess sediments of the higher elevated surrounding Muschelkalk plains thin out and become patchier (Steinmüller, 1996).

2.2. Field research and laboratory methods

Subdivision areas and transects were selected for analysis based on the assumption that both relief and bedrock influence the spatial distribution and properties of PSD. Various heavy-bedded and fine-bedded limestones were compared as well as slope and plain relief situations. Only forest covered areas were investigated to minimise possible transformation of sediment structure caused by soil erosion of anthropogenic land use (see Discussion section).