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Micromorphology in landslide sediments – a different approach for investigating mass movement deposits

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1. INTRODUCTION

The analysis of landslides is commonly based on geomorphological mapping and the analyses of several parameters of soil physics and mechanics. However, information obtained from these methods is limited, especially when used in a complex landslide environment with heterogeneous slide material and different types of movements.

In order to reliably reconstruct a landslide event, specific triggers, movements and the current state in terms of stability, a profound knowledge of the slide masses' inner architecture and internal processes is of great importance. As states, micromorphology permits a complete examination of all components contained in unconsolidated sediments, as well as an insight into their internal arrangement. Compared to other methods, micromorphology generally provides three major advantages, namely (I) an in situ method, that allows studying particles and structures in their original, undisturbed state in relation to each other, (II) provides the possibility of precise compositional and positional analyses, and (III) relates observed structures to specific processes (e.g. movement processes) (van der Meer and Menzies, 2011). Due to these advantages, micromorphology is frequently used in pedology as it is in geology/mineralogy. But in contrast to the extensive external descriptions of movement and sedimentation processes as well as resulting landforms, very little is known concerning the internal movement mechanics and structures of unconsolidated sediments. However, in accordance to 'structural isomorphism', many phenomena observed within thin sections have equivalents at the macro-scale (Hiemstra and Rijsdijk, 2003), and therefore are of significant importance when studying any kind of sediment mass.

It is only in the last decades, that micromorphology proved to be a reliable and integrative method, which was used in many different geo-scientific research questions. Above all, several studies on glacial sedimentary problems were based on micromorphology (e.g. Menzies et al., 1997; Phillips and Auton, 2000; Menzies, 2000; Hiemstra and Rijsdijk, 2003; van der Meer et al., 2003), as were investigations on fluvial sediments (e.g. Mücher and de Ploey, 1977; Maltman, 1988; Menzies and Ellwanger, 2012) or solifluction processes (e.g.

Harris and Ellis, 1980; Hutchinson, 1991; Harris and Lewkowicz, 1993; van Fliet-Lanoe, 2010). Only few studies used micromorphology as a method analysing mass movements (e.g. Bertran, 1993, Bertran et al., 1995, Bertran and Texier, 1999) mainly focusing on debris flows (e.g. Menzies and Zaniewski, 2003; Theler, 2004) or slope deposits in general (e.g. Bertran et al., 1995, Bertran and Texier, 1999). Until today, the micromorphology of (typical) landslide sediments was not studied in detail.

2. MICROMORPHOLOGICAL STRUCTURES IN UNCONSOLIDATED SEDIMENTS

Generally speaking, various micromorphological structures within sediments are generated as a result of pressure, e.g. compression or stress. The response of sediment is similar to the Mohr-Coulomb-Model for isotropic materials (Hiemstra and Rijsdijk, 2003) which describes an elastic deformation as a first reaction. Increasing stresses may lead to plastic deformation and, once the sediment is no longer capable of withstanding the induced pressure, to sediment failure (Hiemstra and Rijsdijk, 2003). In practice, (landslide) sediments are not isotropic, which leads to certain variations in terms of the actual response, influenced by pressure, water and time.

In the case of landslides, these four factors (time, pressure, water and material) may vary greatly: Time differs from several hours to days in the case of an actual landslide event. If creeping (prior or subsequent to the landslide) is included, the time period might extend to months or years. Similarly, the influence of pressure (e.g. stress, shear pressure) on the sediments is variable, with the most intensive forces occurring during the main movement. Depending on water content and sediment properties (esp. grain sizes and heterogeneity), increased or reduced pressures occur inside the landslide material. Accordingly, a more fluent movement (*earth/debris flow*) is due to a (very) high water content (low effective stress), while less water (and therefore higher effective stress) leads to a sliding process (*landslide*, see Varnes, 1978). Lastly, grain sizes in landslide sediments range from fine clay to large blocks. These variations do not only occur between different landslides but also within a single (complex) slide area. As micromorphology is capable of pointing out these different influences, it can be an important tool in the analysis of landslide sediments.

The analysis of thin sections from landslide sediments is similar to the procedures employed for glacial and other unconsolidated sediments (e.g. Carr, 2004; van der Meer and Menzies, 2011). As part of textural analyses, skeleton grains (> 30 µm, visible as single grains) and plasma material (< 30 µm, not individually visible) are described. Structural analyses focuses on depositional and deformation structures, mainly as a type of ‘reconnaissance study’ (Carr, 2004), focusing on identifying structures indicative of deformation (e.g. van der Meer, 1993, 1996; Menzies, 1998, 2000; Bertran and Texier, 1999; Hiemstra and Rijsdijk, 2003).

Structures once detected can be differentiated into various types: for example, planar structures (e.g. lineations) in comparison with rotational structures (sometimes referred to as turbate or galaxy structures). Regarding to the style of deformation, ductile structures (e.g. necking structures), differ from brittle structures (e.g. faults, crushed grains) as well as polyphase structures (e.g. multiple structures) and features, which are significantly influenced by porewater (e.g. water-escape-structures) (see. Fig. 1; van der Meer, 1993; Menzies, 2000; Carr, 2004).

By analyzing those structures in landslide sediments, the influence of the specific factors may be assessed. A ductile or porewater influenced deformation style, for example, can be associated with a high content of water in the sediment, whereas dry conditions lead to more brittle deformation. Rotational structures, represent intense pressure in a broad zone of deformation, while planar structures are induced by discrete shear (Carr, 2004). Furthermore, clayey and silty domains tend to develop specific plasmic microfabrics (see Fig. 1) depending on the intensity and continuity of the induced stress.

Associated deformation structures allow a process-based interpretation of the deformation and the types of movement involved. Insights on the internal architecture give a general idea of the sediments' stability, as density and the spatial arrangement of particles become obvious.

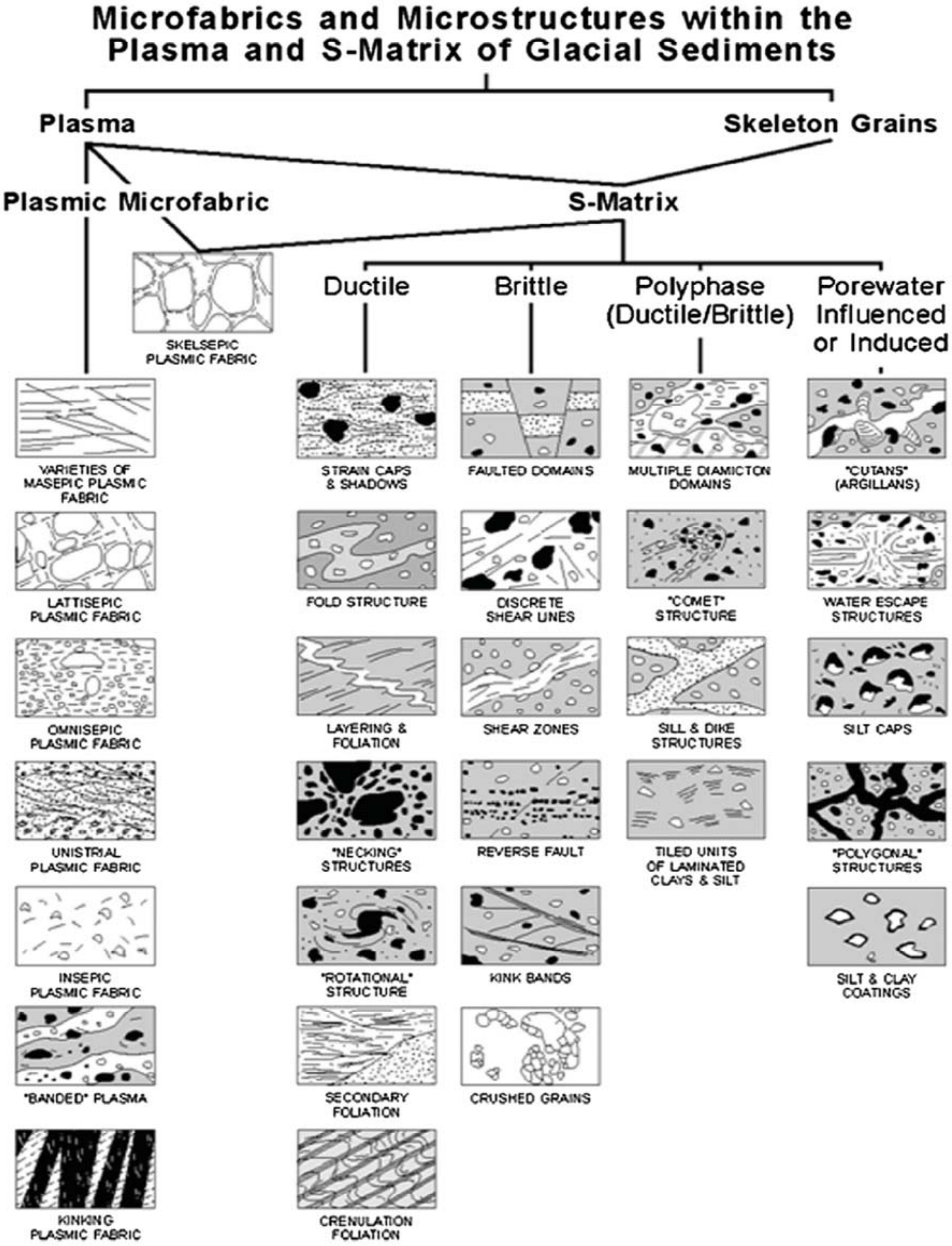

Figure 1: Deformation structures identified in thin sections (Menzies, 2000 after van der Meer, 1993)

3. STUDY SITES

In a first attempt to assess the micromorphology of landslide sediments, samples were taken from two landslide areas in northern Bavaria. The first study site is located near Ebermannstadt in the Franconian Alb, approximately 40 km north of Nuremberg. Geology in the region of Ebermannstadt is characteristic for the structure of the Franconian Alb with permeable (limestone and sandstone) and impermeable (clay, claystone, marl) layers.

Die to past landslides, most slopes in the area are covered with landslide debris. The region around Ebermannstadt was affected by landslides in 1625, 1957 (= study site), 1961 and 1979 (plus several more undated events) all of which reached very close to the city limits. An assumed remobilization of landslide sediments might endanger houses and infrastructure.

A second study area is located near Gailnau, as small village at the Frankenhöhe ridge, approx. 70 km west of Nuremberg. The area is dominated by sandstone covering layers of claystones and marls. Intense weathering of the sandstone in combination with heavy rainfalls appeared to have triggered a landslide in February 1958. Geomorphological mapping described a rotational landslide in Gailnau, whereas the movement in Ebermannstadt originally was more of a translational slide that transformed into a complex movement during the event (Jäger et al., 2013).

Samples were taken from pits (randomly) dug in the upper, central and lower / foot parts of the landslides. All samples were collected at least 40 cm below the surface, marked for orientation and sealed properly. After drying, impregnation and cutting, thin sections were prepared in the laboratory (for details, see Kemp, 1985; van der Meer and Menzies, 2011; Rice et al., 2014).

4. RESULTS

In total, nine thin sections from Ebermannstadt (samples E-1 through E-9) and five of Gailnau (named G-1 to G-5) were analysed. Below follows a brief description of the most prominent results from samples. For a definition of the technical terms please refer to the specific references (e.g. van der Meer, 1993, 1996; Menzies, 2000; Carr, 2004; van der Meer and Menzies, 2011).

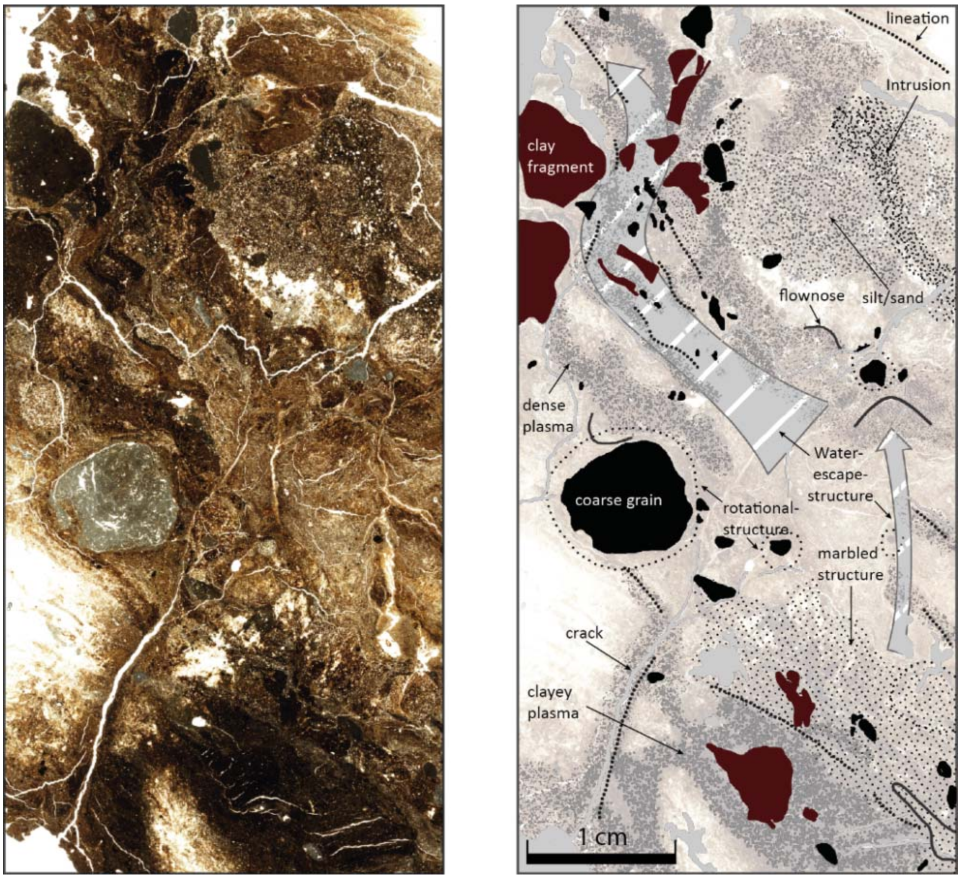

Figure 2: Thin section E-3 (taken at a slide block from Ebermannstadt study site); note several rotational structures and water-escape-structures resulting from intense deformation

Samples from the clayey uphill parts at the slide area in Ebermannstadt are clearly dominated by clayey/silty plasma material with only single grains incorporated. The samples show a distinctive plasmic fabric (unistrial / masepic) which leads to the assumption of a rather constant influence of pressure from the same direction (top), possibly representing a creeping process. Slightly different orientations of the plasmic fabric might be a result of the actual landslide event, during which the sediment was slightly deformed as the covering unconsolidated limestone debris moved downslope. The ductile deformation/behaviour of the material is underlined by the absence of any significant brittle structures.

A much more intense deformation, in general, becomes obvious in samples taken from the foot of a slide block only some forty meters below the previously described samples. Beside plasma material, large amounts of sand and skeleton grains (mostly limestone fragments) are visible in those thin sections. Around several of these grains, rotational structures are well developed.

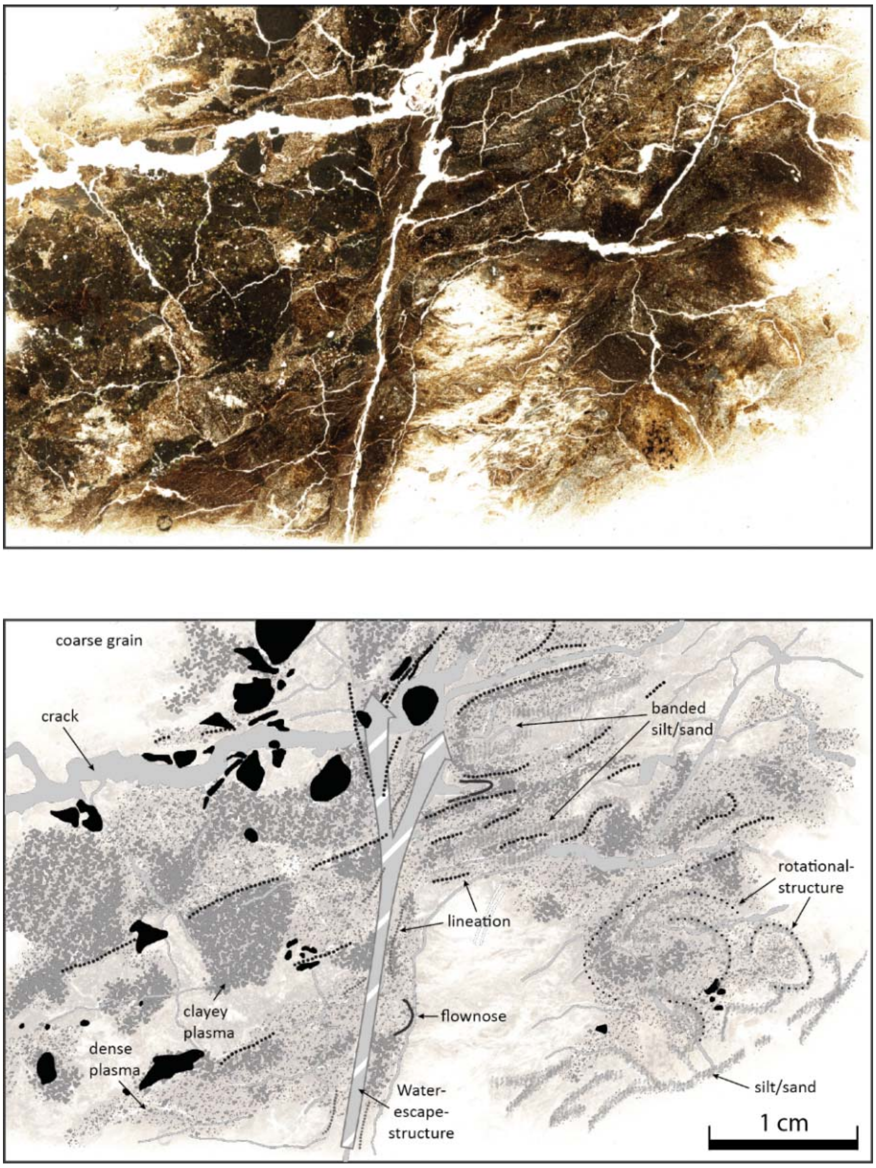

Figure 3: Thin section E-4 (taken at a slide block from Ebermannstadt study site); rotational structures and intercalated/mixed domains indicate ductile deformation, overall less disturbance compared to thin section E-3

The dominant influence of porewater becomes especially obvious in E-3 (Fig. 2), with a large, s-shaped water-escape-structure in the central part of the image accompanied by a second smaller neighbouring one. Both indicate an intensive porewater movement. At the lateral edges of the main water-escape-structure, lineations, small ‘bands’ or silty/sandy domains are deformed and a necking structure is visible as are small flow noses. The main structures in E-3 all are indicative of an intense ductile and/or porewater induced deformation with high pressures from various directions, caused likely by a comparatively quick movement of the heterogeneous slide block. However, as a thin section from nearby (E-4; Fig. 3) as well as samples from Gailnau show, a moving slide mass does not necessarily always produce these intensive deformation structures.

In E-4, rotational structures, small water-escape structures and flow noses still indicate a predominantly ductile influenced deformation, complemented by certain elements of brittle deformation (fractured particles and domains). In contrast, G-1 and G-2 (Fig. 4) exhibit only poorly developed deformation structures in contact areas of the different domains. Therefore, E-4 can still be related to similar processes as described for E-3, but the two samples from Gailnau indicate a completely different movement process which resembles a 'rafting' process as described by Menzies and Ellwanger (2012). Due to much less pressure and a distinct surface of rupture, sediment aggregates have been moved and mixed, creating an almost undeformed mosaic pattern.

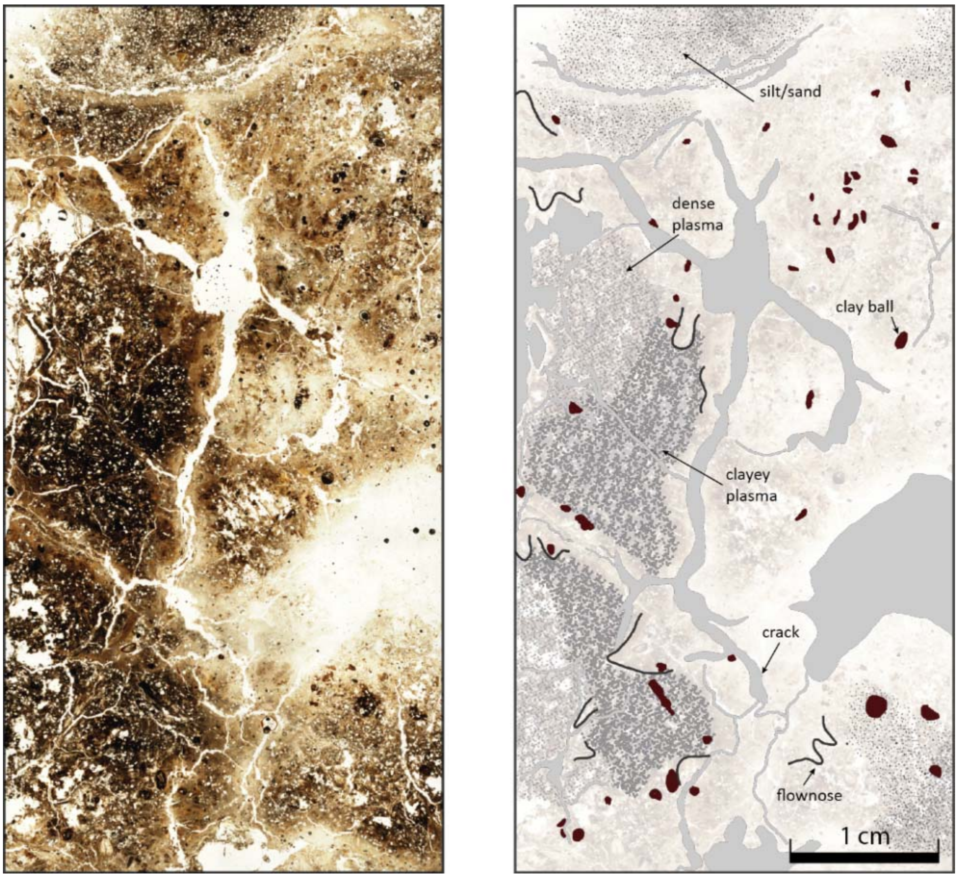

Figure 4: Thin section G-2 (taken from slide mass at Gailnau study site); note intercalated domains only slightly mixed and deformed

In the lower (downslope) parts of the slide mass, thin sections are dominated by a high amount (> 50 %) of coarse grains with diameters up to 1 cm. The occurrence of plasma is mostly limited to seams between the grains. Sharp grain boundaries and numerous crushed grains are common, indicative of brittle deformation. However, surface parallel (to large grains), horizontal or circular orientations of coarse grains also reveal a degree of a ductile influence. That creates an impression of a slide mass dominated by coarse grains with (almost) water saturated plasma material in the pores which led to a maintained movement. As no plasmic fabric was detected, pressure was possibly lower. During stages of sedimentation, deposited material was pressured by sediment masses pushing from areas uphill, leading to dewatering and consolidation of the main slide mass in its lower regions. The result is a subsequent outflow of water saturated, fine grain sediments.

Therefore, foot areas of complex landslides are often shaped by a flow-type of movement. Samples from lowermost foot areas appear almost structureless, as water saturation and the movement "destroyed" previous structures resulting in homogenization of the sediment. Thin sections are dominated by a clayey and silty groundmass, with varying amounts of fine sand incorporated and almost no coarse grains present.

5. DISCUSSION AND CONCLUSIONS

Based upon previous research e.g. on slope deposits (Bertran and Texier, 1999) or debris flows (Menzies and Zaniewski, 2003), two characteristic landslides of the German cuesta were investigated. During our studies, it became obvious, that micromorphology, in general, is a valuable tool in the analysis of landslides and their sediments.

Preparation of thin sections from landslide sediments is similar to glacial or pedogenic samples and the standard procedure for preparing thin sections from unconsolidated sediments is applicable (see e.g. Kemp, 1985; van der Meer and Menzies, 2011, Rice et al., 2014).

Thin section analyses reveals a broad range of deformation structures consistent with the taxonomy of microfabrics and microstructures within glacial sediments as published by Menzies (2000, see Fig. 1). As expected, samples from the two study sites showed microstructures reflecting varying influences of time, pressure, water and material on the sediment. Insights on the internal architecture of the sediments allow an assessment of the impact these factors have had on specific mass movement processes.

Most thin sections were dominated by ductile or porewater induced processes, especially water-escape-structures and flow noses were common. These microstructures reflect a high content of water involved in those slide areas, both in the scarp area and the slide mass. Planar features (mainly lineations) were found in several thin sections, however, rotational structures were more common. Pervasive deformation was also represented by marbled structures (in E-3) which tend to form due to the mixing and deformation of different sediment domains. Marbled and tiled structures (see Menzies and Zaniewski, 2003 for details) are considered diagnostic features in debris flows (Menzies and Zaniewski, 2003). However tiled structures were nowhere found in our studies and marbled structures just once. Intercalation and mixing of different sediments/domains is widespread in landslide sediments. As our investigations show, differences in terms of pressure and porewater may lead to less or increased levels of deformation even within small areas.

Beside ductile or porewater induced deformation forms in thin sections dominated by plasma, brittle structures were evident in samples with an increased amount of coarse grains. Due to the many skeleton grains, brittle deformation structures such as edge-to-edge crushing or crushed grains were noted several places in these thin sections. Faults and well developed shear lines, both common features of brittle deformation in glacial sediments, were not observed. This is supposably due to the fact that landslides provide a relatively short time period for deformation and an inconsistent or turbulent movement.

Generally, despite limited time for development, several structures are visible in landslide sediments, but as yet it is not possible to identify a certain structure as diagnostic for these specific landslides. It remains to be seen if that changes over time, but bearing in mind, that landslides are completely heterogeneous forms in terms of pressure influence, involved sediment material, water content and movement period, one might not find one but several diagnostic structures. As stated above, marbled structures, deformation induced water escape structures as well as intercalated/mixed domains (with varying degrees of deformation) seem to be common in most slide masses, differentiating these landslide sediments from e.g. soil material.

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