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Holocene Sediment Dynamics in the Vicinity of a Roman battlefield near Osnabrück (NW-Germany)

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with 11 figures and 4 tables

Abstract. The interpretation of the Holocene sediment dynamics at Mount Kalkriese in the Wiehengebirge mountains (northwestern Germany) shows that the onset and the extent of human land use corresponds well with most colluvial archives in Central European loess regions: The onset of soil erosion in the Wiehengebirge mountains started during the Early Neolithic period. For the Bronze Age, erosion and colluviation are documented as well. A considerable increase of soil erosion with correlated reworking of colluvial sediments was found since Roman times, indicated by the burial of Germanic artifacts of Roman Age at the toe-slopes. Unfortunately, no absolute ages exist for the post roman period. However, in analogy to other sites it can be assumed that highest erosion rates occurred during the Middle Ages.

This study also shows typical problems when using the soilscape model for calculating the sediment budget: since truncated soil profiles are used to model eroded volumes, only minimum soil erosion is mapped. This can lead to a considerable discrepancy between eroded and accumulated volumes. Therefore, we have to assume that soil erosion at the plateau and in upslope areas at Mount Kalkriese was much higher than predicted by the soilscape model. In addition, extensive anthropogenic accumulation soils (Plaggen soils) were deposited in the downslope areas, thereby increasing the discrepancy between erosion and accumulation volumes.

The combination of mapping erosion and accumulation with augerings and trenches, calculation of the mass balance by GIS, relative and absolute dating and geophysical evidence provides a powerful tool in landscape interpretation. Due to the small number of numerical ages, the landscape model at Mount Kalkriese has to be considered preliminary.

Zusammenfassung. Die Interpretation der holozänen Sedimentdynamik am Kalkrieser Berg im Wiehengebirge (Nordwest-Deutschland) zeigt, dass Beginn und Intensität anthropogener Eingriffe in die Landschaft hier in ähnlichem Ausmaße verlaufen sind wie es bereits viele andere kolluviale Archive der mitteleuropäischen Lössregionen gezeigt haben. Die Bodenerosion begann im Wiehengebirge bereits während des frühen Neolithikums. Auch für die Bronzezeit konnten intensive Umlagerungsprozesse nachgewiesen werden. Ein deutlicher Anstieg der Erosionsdynamik und damit verbundene Aufarbeitung älterer Kolluvien kann für die nachrömische Zeit festgestellt werden. Diese Kolluvien überlagern im Unterhangbereich germanische Funde der Vorrömischen Kaiserzeit. Leider existieren für die nachrömische Zeit keine absoluten Datierungen. Allerdings kann, analog zu anderen Landschaftsarchiven, unterstellt werden, dass der Großteil der Umlagerungen mittelalterlichen Ursprunges ist.

Die Arbeit zeigt auch die methodischen Probleme des Soilscape-Model-Ansatzes. Da für die Berechnung der Erosionsvolumina gekappte Bodenprofile verwendet werden, kann nur ein Minimalwert für die Bodenerosion ermittelt werden. Daher ist zu vermuten, dass die Erosion auf der Kuppe des Kalkrieser Berges erheblich höher war als durch das Modell vorhergesagt. Des Weiteren wurden anthropogene Auftragsböden (Plaggenesch) im Unterhangbereich aufgetragen, die den Sedimentüberschuss zusätzlich erhöhen.

Die Kombination von Erosionsbilanzierung durch Bohrungen und Profile, die Ermittlung der Massenbilanz durch GIS, relative und absolute chronologische Befunde und geophysikalische Methoden ermöglicht eine umfassende Interpretation der Landschaftsentwicklung. Die geringe Anzahl unabhängiger Datierungen erlaubt allerdings nur eine vorläufige Rekonstruktion der Landschaftsentwicklung.

Keywords: Holocene sediment budget, geoarchaeology, landscape evolution, colluvial deposits, soil magnetic susceptibility, soilscape model

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1 *Introduction*

Colluvial deposits as archives of Holocene landscape development and human impact have become a prominent subject of research within the last decades. In Central Europe most work focuses on the Belgian Loess Belt (Rommens et al. 2005, Rommens et al. 2006, Rommens et al. 2007), Southern Germany (Dotterweich 2003, Leopold & Völkel 2007, Lang 2003, Lang & Hönscheidt 1999, Houben 2008), Central Germany (Bork et al. 1998) and the extreme north of Germany (Reiss et al. 2009, Dreibrodt 2005). Until today, no research has focused on the margins of the northwestern German low mountain ranges (Dreibrodt et al. 2010, Dotterweich 2008).

In general, the change from hunters and gatherers to an agricultural society during the Early Neolithic was delayed in the northwestern German lowlands, while the northern margins of the low mountain range Wiehengebirge were characterized by a quite early and continuous settlement (cf. Möllers 2004). Various studies throughout Central Europe indicate that Neolithic settlement activity and the onset of agricultural land use since about 7.5 ka cal BP strongly correlate with initial Holocene soil erosion and colluviation (Bork et al. 1998, Dotterweich 2008, Dreibrodt et al. 2010).

In our research area, the remains of the Roman-Germanic Varus Battle (9 AD) are well examined but information on Germanic settlements is sparse due to the low density of archaeological findings and the low persistence of settlement remains (Moosbauer 2009, Wilbers-Rost 2007). Accordingly, one of the main open questions is about land use and settlement density in the larger conflict landscape at Mount Kalkriese. Various items, such as the existence of a Germanic settlement at Schwagstorf close to the battle site dating back to Roman times, support the hypothesis that this area was a fairly densely populated area with intensive agricultural land use during Roman times. Due to the lack of conclusive evidence for extent and intensity of land use in the surrounding area it is of particular interest whether the analysis of colluvia can give evidence for land-use activities during Germanic-Roman times.

In this study, onset and extent of human land use and its influence on historic soil erosion are analyzed. Mapping of soil erosion, including a quantification of the volumes of colluvia, were combined with absolute and relative dating. This allows the first reconstruction of landscape dynamics in this area of high archaeological importance.

2 *Geographical setting*

The research area is located in Northwestern Germany approximately 15 km north of the city of Osnabrueck at the transitional zone from the central German uplands to the northern lowlands (Fig. 1). At this location, the hilly area of the Wiehengebirge mountains projects into the lowlands with a WNW-ESE axis. The Wiehengebirge mountains are composed of Jurassic sandstones and mudstones with varying carbonate contents (Klassen 1984).

Mount Kalkriese is an outlier of the Wiehengebirge mountains projecting approximately 4 km into the northwestern lowlands, covering an area of about 15 km^2. Its maximum altitude at the top plateau is at 153 m a.s.l. while the northern lowlands only reach 50–55 m a.s.l. The steepness of some deeply incised valleys can exceed 50 %, while the agriculturally used hill slopes show an average steepness of about 5–12 %.

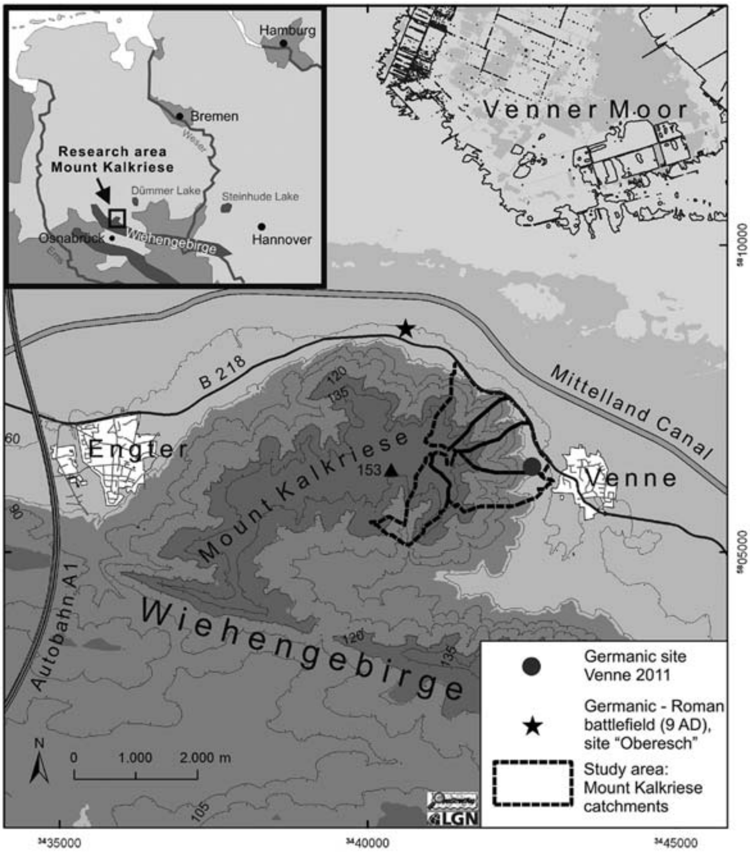

Fig. 1. Mount Kalkriese is an outlier of the Wiehengebirge low mountain ranges projecting into the northwestern German lowlands. The Germanic – Roman battlefield of 9 AD is located in the north of this natural bottleneck between steep mountainous areas and the adjacent peat bogs of the Venner Moor.

The northeastern slopes of the Wiehengebirge mountains were typical locations for Late Pleistocene to Early Holocene loess deposition. Large amounts of loess were transported from the permafrost plains of northern Germany by northeasterly winds and deposited at the topographical barrier of the Wiehengebirge mountains. According to BETZER (2003) the main phase of loess accumulation took place during the Weichselian glacial maximum. Corresponding to the complex relief of the hilly country, the thickness of the sandy loess sediments in the research area varies between 1 and 8 m: Whereas the thickness of the loess cover can reach several meters in middle and downslope positions, only a small amount of loess was deposited on the exposed plateau areas. Due to weathering processes, the formerly carbonate rich sandy loess was decalcified and transformed into sandy loess loam today. The gently rolling northeastern flanks of the mountains are fan-shaped and dissected by steeply inclined valleys, whereas the ridges are covered with loess loam of varying thickness.

The dominating soil types on the silty-loamy slopes are luvisols and stagnic luvisols (FAO 1989), corresponding to Parabraunerden and Pseudogley-Parabraunerden with partly low degrees of lessivation following the German soil nomenclature (Ad-Hoc AG Boden 2005). On sandier foot-slope positions colluvisols are frequent. According to the official soil map (LBEG 2009), Plaggen soils cover nearly 20 % of the downslope areas and of the surrounding lowlands (cf. Eckelmann 1980). Plaggen soils are anthropogenically formed accumulation soils which can be found in the sandy lowlands of Denmark, NW Germany, Belgium and the Netherlands. To increase or maintain cropland fertility, organic soil horizons were excavated from forest and grassland areas and brought as litter to the cattle sheds. Subsequently, the nutrient-rich mix of plant material and manure was transported to the cropland. This form of land use can be traced back to the late Bronze Age and was continued until the last century. In the FAO classification these soils are classified as Plaggic Anthrosols (Blume & Leinweber 2004).

Archaeologically, the transitional zone between the low mountain ranges of the Wiehengebirge and the Northwest German lowlands has an old and continuous settlement history. Numerous megalithic grave sites nearby and a permanent settlement at Lake Dümmer (Fig. 1) give evidence of continuous settlement and farming activities in the area from the Neolithic period until the Pre-Roman Iron Age (Möllers 2004, Leuschner et al. 2007). In 9 AD, the so-called Varus Battle was fought in this area, resulting in the defeat of three Roman legions and the death of approximately 15,000 Roman soldiers. This defeat effectively stopped the expansion of the Roman Empire in the areas east of the Rhine River. Hence, the Kalkrieser-Niewedder lowland at the foot of Mount Kalkriese as the location of the Varus Battle (Fig. 1) was subject of intense archaeological research (Harnecker & Tolksdorf-Lienemann 2004, Moosbauer 2009, Wilbers-Rost 2007). The final stages of the battle at the Kalkrieser-Niewedder lowland are well documented since its remains were covered and thus preserved by colluvisols (Rost & Wilbers-Rost 2011). Since the settlement density of Germanic tribes in the region during this conflict is not known yet, most recent archaeological research in the area was focused on Germanic settlement structures. Thus, in 2011 a large archaeological site near Venne was excavated at the toe-slope of our research area (Figs 1, 2).

3 *Methods*

During this research, mapping of soil erosion and accumulation based on augerings and trenches is the basis for the calculation of a sediment budget of the Holocene. The sediment balance for each augering is determined by a comparison with a reference-luvisol. Subsequently, geostatistic modeling and interpolation in GIS-software allowed the calculation of the mass balance in the research area. Chronological determination of the relocation processes was realized by dating with optically stimulated luminescence (OSL) and stratigraphic correlation with archaeological sites. Furthermore, the results of the landscape model were backed by geophysical evidence.

3.1 Field methods

In order to calculate the mass balance for the research area, five catchments (Fig. 2) have been examined. These investigations were the base to establish a sediment budget and to determine

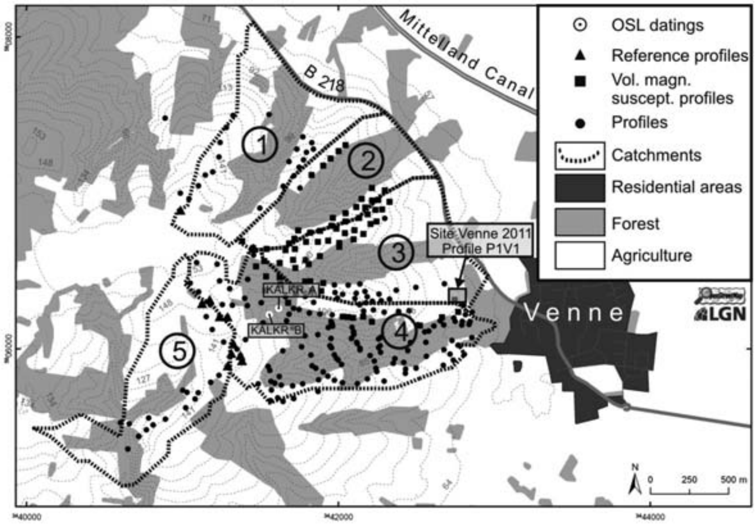

Fig. 2. The study area of Mount Kalkriese with the five examined catchments. Agriculture is dominant on gentle slopes, whereas steeper valleys are covered with forest. The two locations for OSL dating (KALKR A and B) are located in a valley. The archaeological site of Venne 2011 is located on a field.

the onset of anthropogenically induced soil-erosion, in order to enhance the knowledge about Germanic settlement activity in this area of outstanding archaeological interest. For this purpose, 266 auger corings were carried out using Edelmann and Puerckhauer hand augers. Generally, the distance between two corings was set at 30 to 90 meters, whereas selection of the coring-sites followed geomorphological criteria: In areas of higher topographical variability coring density was higher, whereas at gentle toe-slopes with fairly homogeneous conditions augering density was reduced (Fig. 2). Augering positions were determined using a Garmin eTrexH-GPS system. Augering depths varied between 0.2 m on heavily eroded slopes and more than 3 m on toe-slopes.

During field work, the cores were described according to the German Soil Survey Manual (Ad-hoc Arbeitsgruppe Boden 2005). Special care was taken in the collection of the data concerning the upper and lower limits of soil horizons, texture and soil skeleton, Munsell soil color and hydromorphic features. Additionally, the occurrence of specific items such as charcoal fragments, stones, pieces of pottery or large organic fragments was noticed and they were collected separately. At 73 soil profiles the magnetic susceptibility of each soil horizon was measured in replicates using a Bartington MS3 meter equipped with a MS2 K probe. The average of two measurements was then used to describe the magnetic susceptibility of each section. From each horizon small soil samples were collected in plastic film containers for analysis in the laboratory.

3.2 *Laboratory work*

In order to check the accuracy of the field methods 32 soil samples were collected at the newly excavated archaeological site Venne at the toe-slope of Mount Kalkriese in 2011 (Fig. 2). The soil samples of profile P1V1 were examined in the laboratory of the Department of Geography, University of Osnabrueck. Grain size distribution was determined using the combined sieve-pipette method following SCHLICHTING (1999). Organic content (LOI) was determined gravimetrically according to DEAN (1965) by heating the samples for 4 hours at 550 °C in a muffle oven. The quality of laboratory analyses was ensured by carrying out replicate and triplicate measurements. Samples with an error of more than+/- 10 % were discarded. Since the sediment is decalcified due to weathering processes, the loss of carbonate during the heating process can be neglected. Only for clay illuviation horizons higher inaccuracies of LOI measurement due to the loss of crystal water have to be taken into account.

3.3 *OSL dating*

Samples for OSL dating were taken from two profiles (KALKR A and KALKR B) representing each soil horizon and/or sediment layer. Sampling during night and storage in opaque plastic bags prevented the material from exposure to any light. In parallel, material was sampled to determine the content of radionuclides. From this material, the total dose rate was calculated based on the specific activity of nuclides from the decay chains of ^{238}U, ^{232}Th and ^{40}K, measured with low-level gamma-spectrometry in the Felsenkeller laboratory of the VKTA Rossendorf in Dresden. The contribution of cosmic radiation to the total dose rate was estimated due to the geographical position of the profile, its altitude above sea level and the sediment cover of the sampled layer. Corrections of the dose rate-efficiency involved the mineral density of the dosimeter quartz, the density of the surrounding sediment and its palaeo-water content. The latter was calculated using the field moisture capacity of loess and allowing the water content to vary within 20 %.

OSL-samples were prepared and measured at the luminescence laboratory of the TU Bergakademie Freiberg. The separation of material for single-aliquot OSL-measurements of quartz coarse-grains included: sieving to 100–200 µm, removal of carbonates (HCl 10 %) and organic material (H_2O_2 30 %), feldspar flotation (HF 0.2 %, H_2SO_4, dodecylamine, HCl 5 %), density separation (sodium polytungstate, 2.62 and 2.67 g/cm^3), etching (HF 40 % for 45 min., HCl 35 %) and final sieving to 90–160 µm. Medium aliquots (200–500 grains) of the quartz separate were measured using a Risø DA 20 OSL/TL reader equipped with a Sr-90 beta irradiator (5.6 Gy/min). The OSL emission was stimulated with blue LEDs (470 nm, 90 %) for 50 s at 125 °C, and detected through a U 340 Hoya optical filter.

Equivalent doses of each aliquot were determined using the single-aliquot regenerative dose (SAR) protocol according to MURRAY and WINTLE (2000), including the control of recuperation, recycling ratio and sensitivity changes. The reliability of the applied measurement procedure and material properties was assessed in dose recovery tests (MURRAY & WINTLE 2003). Indication about the degree of bleaching was inferred from the distribution of equivalent doses: Paleodoses were calculated based on the arithmetic mean for samples with symmetric dose distributions and low standard deviations. Asymmetric dose distributions with high standard deviations indicated the presence of residual signals due to insufficient bleaching during sediment transport or reworking. Hence, statistical procedures had to be applied to detect and exclude residual signal components (e.g. MURRAY et al. 1995, OLLEY et al. 1998, MURRAY & OLLEY 2002, FUCHS & LANG 2001, BAILEY & ARNOLD 2006, RODNIGHT et al. 2006, DULLER et al. 2008). For small data sets and/or samples with homogeneous insufficient bleaching the statistical exclusion of residual signal components was not possible. Therefore, only maximum ages could be derived from such samples that are based on the arithmetic mean.

3.4 *The soilscape model*

Soil loss and corresponding volumes of colluvial deposits for areas in Central Europe covered with luvisol can be calculated using different approaches: On the one hand, truncated soil horizons are suitable to calculate volumes of eroded material. However, this can lead to an underestimation of soil loss on heavily eroded locations. Thus, at these locations only the minimum value of erosion is recorded. On the other hand, measuring volumes of colluvial deposits generally offers more reliable data, but sediments that have left the catchment cannot be detected with this method (Leopold & Völkel 2007).

During this study, eroded sediment volumes were calculated using the soilscape model approach which is a well-established method in sediment balancing (cf. Houben 2008, Bork 1983, Bork & Lang 2003). Rommens et al. (2005, 2006) applied this approach for the Belgian loess belt, which combines both truncated soil profiles and thicknesses of colluvial deposits. The model is based on three assumptions as working hypotheses that were slightly modified to fit the conditions of the Mount Kalkriese area:

1) Rommens et al. (2005) assume that soil development in non-erosive circumstances is independent of slope gradient and aspect. Consequently, the original Holocene soil not affected by erosion is considered as homogeneous and should show identical soil profiles on the plateau and on the slopes. This hypothesis can be transferred directly to the research area.
2) The decalcification level at the Belgian Loess Belt is at 2.3 m. This hypothesis cannot be transferred to the research area since no calcic Cv-horizons were found.
3) The depth of the upper limit of the clay illuviation-horizon (Bt) was estimated at 0.4 m and the depth of the lower limit at 1.5 m, calculated from 14 reference profiles in flat topographic locations. With minor changes, this hypothesis can be transferred to our research area: augerings in flat topographic locations indicate an upper level of the illuviation horizon (Bt) at 0.6 m. The difference between our data and the data for the Belgian Loess Belt can be explained by the coarser grain size of the sandy-silty sediment in Germany, resulting in faster and more effective translocation processes during pedogenesis.

In order to calibrate our soilscape model, 11 reference profiles at flat topographic locations (< 3 % slope angle) on the loess plateau (see Fig. 2) were chosen. Soil profiles at the toe-slopes covered by colluvial layers support an average upper limit of the clay illuviation horizon at 0.6 m depth.

Fig. 3 shows three representative soil profiles to illustrate the soilscape model approach: Core 202 is one of the reference profiles with an upper limit of the clay illuviation horizon (Bt) at 0.62 m. Core 117 shows a truncated soil profile with an upper limit of the Bt at 0.40 m, indicating a soil loss of 0.22 m. At the colluvial profile of core 133 the upper limit of the Bt horizon is located at 0.86 m, indicating a net soil gain of 0.24 m.

A general problem using the soilscape model for the calculation of soil erosion is the underestimation of strongly eroded soil profiles: This is caused by the fact that soil truncation that exceeded the Bt-horizon cannot be documented. Furthermore, at slightly eroded locations tilling can mix up remnants of the Al-horizon with the underlying Bt-horizon.

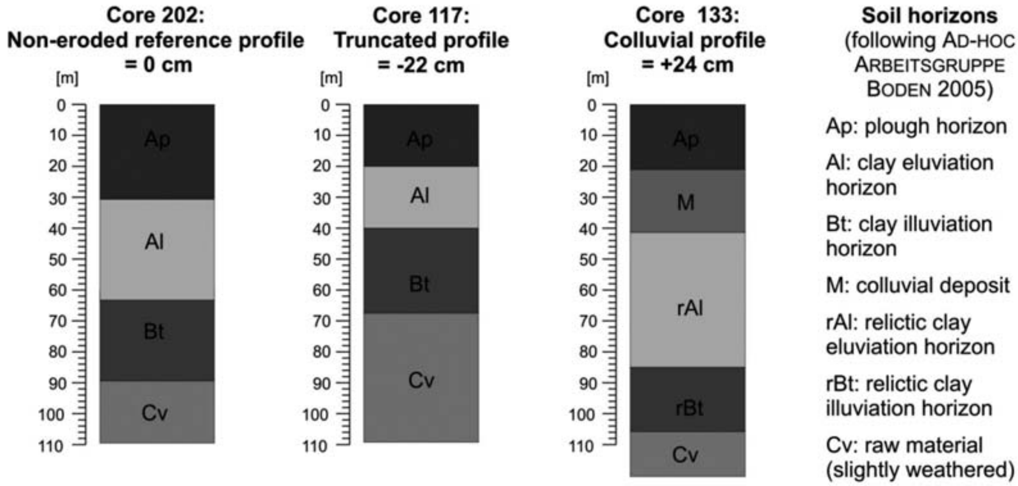

Fig. 3. Representative soil profiles for each setting: not eroded reference profile, one erosional and one accumulation profile.

3.5 *Geostatistical calculations, interpolation and mass balance*

Delineation of the catchment areas was realized using digital elevation model data (DEM) and the basin function in ArcGIS 10's spatial analyst. Since the field findings revealed that even steep valley flanks show less erosional features than the shallow slopes under intense agricultural use, we can assume that in our research area relief seems to be a minor factor for erosion and sediment thickness (cf. Bork 1983). In contrast, the most important factor for erosion is past and present land use. Hence, a reasonable statistical spatial relation between two data points is given, without regard to the geomorphological situation.

The point data of soil loss were interpolated using ordinary Kriging: Kriging is an interpolation method using the theory of spatial variables. In order to compare the results of the interpolation, different IDW (Inverse Distance Weighting with weighing factors of 1.0, 1.5 and 2.0) interpolations were also applied. For the interpolation only profiles with consistent data and unequivocal luvisol features were selected.

For the Kriging interpolations geostatistic models were developed using VarioWin software. As shown in the semivariograms, spherical models showed the best fit. The data of this geostatistic model were then used as input for ordinary Kriging in the ESRI ArcMap 10 GIS software that was done using the default settings for ordinary Kriging: These included variable search radius and interpolation within the nearest 6 points, whereas the output cell size was set at 10.0 m. The accuracy of the Kriging prediction is displayed in semivariograms. Parts of the grid processing were carried out using GRASS GIS. Areas affected by anthropogenic impact like modern roads and settlement areas were excluded from the cut-and-fill-processes using map algebra processing. Moreover, the interpolation data were clipped according to the catchment limits. The same parameters and masking procedures were applied for the IDW interpolations.

The results of the masked interpolation were then used to reconstruct the pre-erosional surface: For this purpose, the inverted absolute values of soil loss respectively soil accumulation were added to the DEM of the recent surface by map algebra. By using the cut-and-fill function in ArcMap 10 areas and corresponding volumes of erosion and accumulation were calculated.

4 *Preliminary results and discussion*

4.1 *Sediment budget for the entire research area*

A total number of 266 augerings in the entire research area was used for this interpolation (Fig. 4). For the Kriging interpolation, a spherical model offers the best fit. The semivariogram shows moderate continuity of the data, resulting from large differences between nearby pairs of drilling points and corresponding high spatial variability of the sediment balance. The treshold value of the applied spherical model was reached at a range of 670 m. Values exceeding this range can not be predicted by the model since their spatial relation is uncertain (cf. Akin & Siemes 1988).

Principally, the entire area of 3.383 km^2 could be used for sediment budgeting, but due to low data availability and high variance within the downslope colluvia the results of the Kriging interpolation were masked to fit a variance limit of 0.18. This variance limit was conservatively chosen due to the field experience with regard to the spatial distribution of colluvial deposits.

After the masking process, a total area of 2.59 km^2 could be used for calculating the sediment budget in the research area. Due to the interpolation process, the absolute values shown in the raw data were smoothed. For the visualization in Fig. 5, the Kriging results were classified manually into 6 classes.

Fig. 5 shows that the upslope areas are generally severely eroded while the downslope areas are covered by mighty colluvial layers. From the map it is also obvious that the size of the erosion area is smaller than that of the accumulation area. This phenomenon itself is not a problem since the depth of soil erosion can exceed the thickness of downslope colluvial layers. However, as shown in Table 1, the calculated volumes of accumulated material exceed those of eroded material by a factor of 3.2 to 4.8, depending on the interpolation method employed. The comparison of Kriging with different IDW weighting factors shows a good fit between ordinary Kriging and IDW 2.0, in accordance with other studies (Rommens et al. 2005, Härtling 2000).

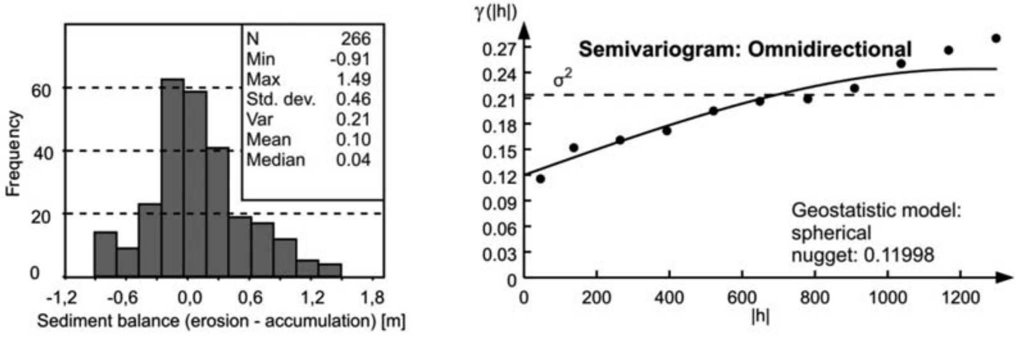

Fig. 4. Statistics of the raw data and semivariogram for the kriging interpolation of the entire catchment.

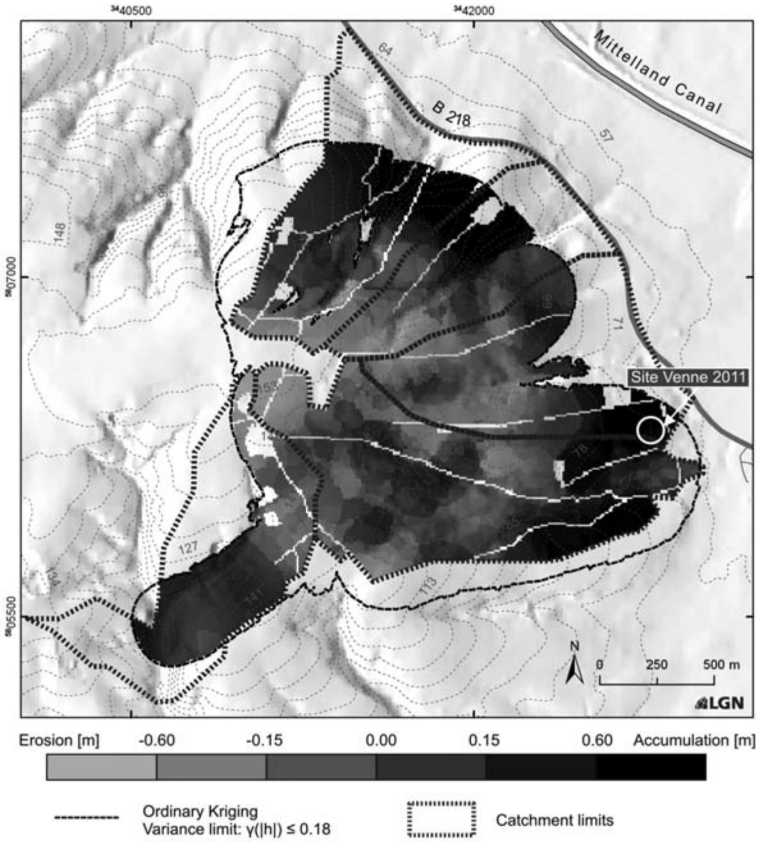

Fig. 5. Result of the Kriging interpolation of soil loss and accumulation for all examined 5 catchments in the Mount Kalkriese area, based on the geostatistical model. To increase the prediction quality, the results of the interpolation were masked to a variance limit of < 0.18.

Table 1. Results of the sediment balance for different interpolation methods. The total areas differ due to masking procedures and/or methodological reasons. In each interpolation volumes of accumulated material exceed those of eroded material.

Interpolation method	Total Area (km^2)	Eroded volume (m^3)	Accumulated volume (m^3)	Ratio accumulation/erosion
Ord. Kriging	3.37	166,424	800,872	4.8
Ord. Krig, Var < 0.18	2.59	151,877	487,282	3.2
IDW 1.0	3.00	175,495	632,218	3.6
IDW 1.5	3.00	189,949	651,014	3.4
IDW 2.0	3.00	205,256	670,662	3.3

4.2 *Sediment budget for one individual catchment*

Since the interpolation results for the entire research area were not satisfying, the process was repeated for the largest catchment (No. 4, Fig. 2) where data availability is higher. A total number of 142 soil profiles was used for the same interpolation methods that were applied for all catchments. For the individual catchment, the semivariogram (Fig. 6) shows moderate continuity of the data again. Once again, a spherical model showed the best fit and the treshold value was reached at a range of 640 m. Values exceeding this range did not underly a statistical spatial relation (following Akin & Siemes 1988).

For catchment No. 4, the interpolations cover an area of 0.94 km^2. The variance limit of 0.18 does not cut the Kriging interpolation results (Fig. 7). Again, the absolute values shown in the raw data were smoothed due to the interpolation process. The Kriging results were classified manually into 6 classes.

By using the cut-and-fill-function the mass balance could be calculated. Again, results of the Kriging interpolation were compared with different IDW interpolations.

As shown in Fig. 7, highest amounts of erosion and accumulation were found in the gently rolling hills affected by agricultural use. In difference, the steep and forested valley sections do generally show only low degrees of sediment relocation. However, again volumes of accumulated material exceed the amount of modeled erosion by a factor 2 to 2.5, depending on the interpolation method applied (Table 2).

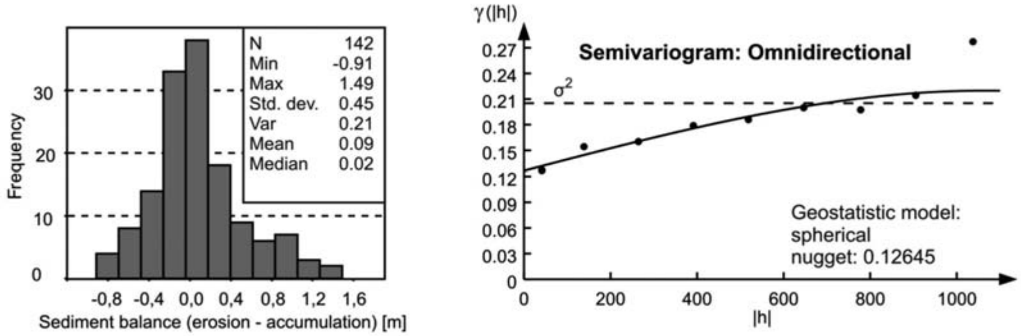

Fig. 6. Statistics of raw data and semivariogram for catchment No. 4, the biggest catchment in the study area.

Table 2. Sediment balance results for different interpolation methods within the largest catchment of the study area (No. 4). In each case accumulated volumes exceed those of eroded material, although the factor is significantly lower than for all catchments.

Interpolation method	Total Area (km^2)	Eroded volume (m^3)	Accumulated volume (m^3)	Ratio accumulation/erosion
Ordinary Kriging	0.94	58,743	146,774	2.5
IDW 1.0	0.94	63,667	149,548	2.3
IDW 1.5	0.94	70,449	152,396	2.2
IDW 2.0	0.94	77,323	156,172	2.0

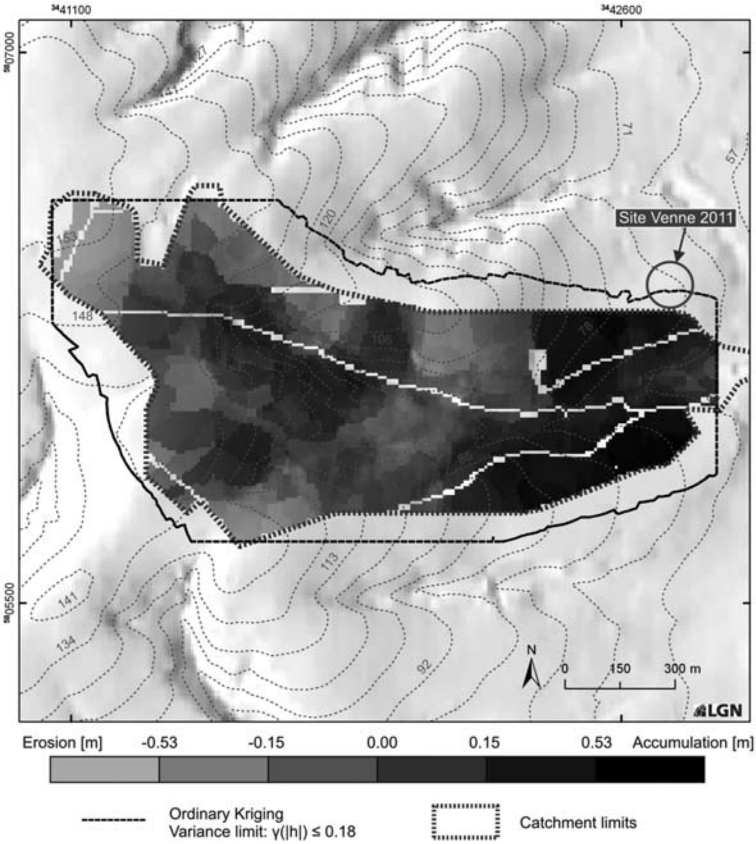

Fig. 7. Kringing results for the largest catchment No. 4. The variance of < 0.18 is realized in the complete area of interest. Again, the area of colluvial deposits is larger than the corresponding areas affected by erosion.

It is obvious that the discrepancy between eroded and accumulated volumes is much smaller compared to the interpolation of the entire research area. However, a considerable gap remains, particularly if sediment outflow from the catchment is taken into account.

The high discrepancy between eroded and accumulated volumes can possibly be explained by the following assumptions:

- Soil loss cannot be mapped exactly by augerings and is likely underestimated at severely eroded locations (Leopold & Völkel 2007). Hence, only a minimum factor of soil loss can be documented with the applied method. Since the loess sediments at Mount Kalkriese are completely decalcified, the decalcification depth (Rommens et al. 2005, 2006) cannot be applied to enhance the accuracy of erosion mapping.
- Recent luvisols at the plateau areas are weakly developed and show relatively low degrees of clay illuviation into the Bt-horizons. If this is interpreted as evidence for a quite young age of the luvisols, the original Holocene luvisols must have been eroded at the onset of agricultural land use during the Early Neolithic period. After erosion and intermediate storage at the

middle slopes the material was reworked following the sediment cascade model by LANG & HÖNSCHEIDT (1999). Today, these colluvial deposits are found in the downslope areas.

- As mentioned above, another cause for the high amounts of accumulated material may be anthropogenic sediment input in the form of plaggic anthrosols in the downslope areas (ECKELMANN 1980, LBEG 2009).

4.3 *Age of the sediments*

Results of gammaspectrometric measurements revealed relatively consistent specific activities between the sampled layers of each profile (cf. Table 3), whereas the concentration of radionuclides is slightly higher in profile KALKR B. No disequilibria are indicated in the ^{238}U decay chain.

All OSL-samples show good luminescence properties with bright and fast decaying signals. Low uncertainties of the dose-signal ratio are indicated by low errors (< 10 %) of exponential curve fit, constant recycling ratios, low sensitivity changes and hence low errors of estimated equivalent doses. Good signal reproducibility during dose recovery tests suggests low sample-specific variations (v_{DR}) of 4–8 % (maximum 14.2 %, cf. Table 4). Equivalent dose distributions are symmetric and show low standard deviations (sd, cf. Table 4). However, compared to dose recovery tests the sd exceeds the v_{DR} by 3–5 %. This could be attributed to microdosimetric variations in the sediment and other post-depositional effects. Therefore, no inhomogeneous bleaching could be detected, apart from sample Kalk-B-OSL3 where a higher sd reveals the presence of a residual signal component. However, OSL ages between 12 and 13 ka from profile KALKR B do not reflect any clear age-depth relation even though pedological findings reveal clearly different sediment features of these sediment layers. Thus, although inhomogeneous bleaching could not be detected for the upper two samples Kalk-B-OSL1 and Kalk-B-OSL2, a masked insufficient bleaching is assumed. Such uniform insufficient bleaching could be caused by generally low light exposure during sediment reworking or dislocation. This could be resulting in age overestimation. Hence, due to the lack of information about the degree of insufficient bleaching, all ages from profile KALKR B are interpreted as maximum estimates. In contrast, OSL ages from profile KALKR A do not reveal any signs of insufficient bleaching and show a consistent relation of increasing ages with depth.

Table 3. Estimates for dose rate calculation (soil horizon: notation due to AD-HOC-ARBEITSGRUPPE BODEN 2005).

KALKR A	Soil horizon	Sediment cover (cm)	Cosmic dose rate (mGy/ka)	^{238}U (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)	^{137}Cs (Bq/kg)
Kalk-A-OSL1	M	30	204	21.7 ± 0.8	20.0 ± 0.7	407 ± 21	< 0.29
Kalk-A-OSL2	M	50	198	25.5 ± 2.7	20.6 ± 0.7	412 ± 21	< 0.34
Kalk-A-OSL3	M	70	193	22.4 ± 2.5	19.1 ± 0.7	358 ± 19	< 0.56
Kalk-A-OSL4	Al	95	186	19.1 ± 1.7	18.9 ± 0.6	349 ± 18	< 0.25
KALKR B							
Kalk-B-OSL1	M	20	207	24.0 ± 2.2	26.0 ± 0.9	453 ± 24	< 0.58
Kalk-B-OSL2	Al I	35	202	23.4 ± 1.1	22.0 ± 0.8	458 ± 16	< 0.45
Kalk-B-OSL3	Al II	90	187	26.3 ± 1.2	25.6 ± 0.8	478 ± 25	< 0.54

Table 4. OSL measurement results and corresponding sedimentation ages (sd: standard deviation, vDR: coefficient of variation in dose recovery tests, (OSL age in brackets): assumed insufficient bleaching).

KALKR A	dose rate (Gy/ka)	paleodose (Gy)	sd (%)	v_{DR} (%)	age (ka)
Kalk-A-OSL1	1.8	5.4 ± 0.1	19.2	14.2	3.0 ± 0.3
Kalk-A-OSL2	1.9	8.2 ± 0.2	10.1	7.2	4.4 ± 0.5
Kalk-A-OSL3	1.7	12.2 ± 0.3	9.8	5.4	7.4 ± 0.9
Kalk-A-OSL4	1.6	20.1 ± 0.5	11.2	8.1	12.8 ± 1.4
KALKR B					
Kalk-B-OSL1	2.0	24.9 ± 0.5	5	4.2	(12.4 ± 1.4)
Kalk-B-OSL2	2.0	25.8 ± 0.6	4.8	4.2	(13.2 ± 1.4)
Kalk-B-OSL3	2.1	27.4 ± 0.8	12.9	5.2	(13.1 ± 1.4)

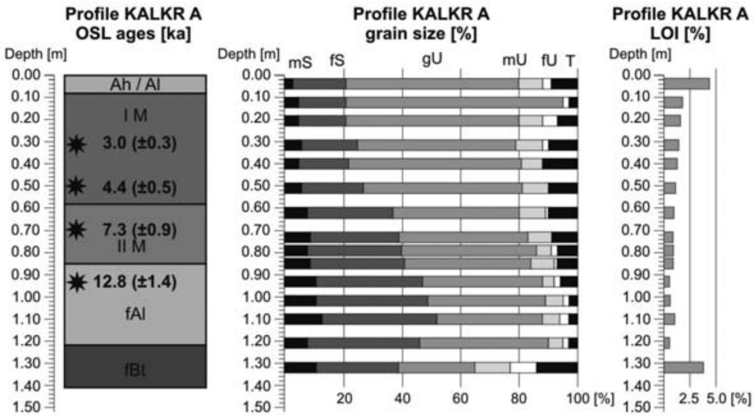

Fig. 8. Profile KALKR A with OSL ages, grain size and LOI. High LOI values in the clay illuviation horizon (Bt) can be explained by water in the clay minerals.

Profile KALKR A (Fig. 8) is located in a valley bottom. For the clay eluviation horizon (Al) an age of around 13 ka was obtained. However, this date does not match with the maximum loess accumulation during the Weichselian maximum (Betzer 2003). A possible explanation for this age discrepancy can be the reworking of accumulated loess material by solifluction processes during the Younger Dryas.

The oldest colluvial sediments in profile KALKR A (0.7 m depth) date back to 7.3 ka, corresponding to the Late Mesolithic-Early Neolithic period. This age corresponds well with the results of other studies in southern and central Germany (Dotterweich & Dreibrodt 2011, Lang 2003, Lang & Hönscheidt 1999, Lang & Wagner 1996, Semmel 1995, Wunderlich 2000). But, however, this is the first dated colluvium in northern Germany within this time slice (cf. Reiss et al. 2009), stating that first soil erosion and corresponding slope deposition in the Mount Kalkriese area started during the Late Mesolithic period, probably by early deforestation and intensified land use. The upper colluvial layer is dated at 4.4 ka (0.5 m depth). This marks the transition between

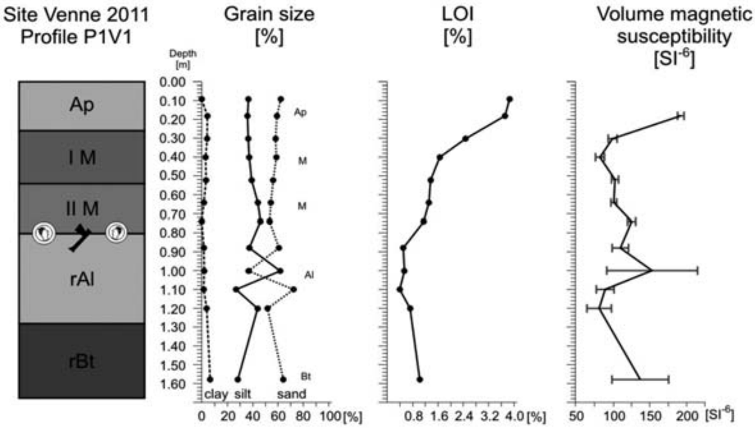

Fig. 9. Exemplary profile P1V1 at the archaeological site Venne 2011. The paleosurface is characterized by archaeological findings of the Germanic-Roman period around the year 9 AD. Overlying colluvia show homogeneous grain size distributions and increased LOI values. The variance of in-situ volume magnetic susceptibility measurements of each soil horizon/sediment layer indicates high interferences close to the paleosurface due to anthropogenic activity.

the Neolithic and Early Bronze Age. Intensified relocation dynamics towards the end of the Neolithic period are reported for several southern German colluvial records as a result of a second maximum of land use intensity (Lang 2003). In contrast, existing northern German colluvial records indicate a first maximum of soil erosion due to intensified agricultural land use within this period (Reiss et al 2009, Dreibrodt et al. 2010). For the surroundings of Mount Kalkriese, the adjacent lowlands were subject to peat bog growth due to more humid climatic conditions, making the former farmlands inaccessible (Leuschner et al. 2007, Eckstein et al. 2010, Bauerochse & Metzler 2001). This could have triggered the more intense land use in the hillslope areas of mount Kalkriese, resulting in increased relocation of soil material. The youngest colluvial deposit within the profile KALKR A is dated at 3.0 ka (0.3 m depth), indicating an Early Iron Age. Intensified soil erosion processes during the Late Bronze Age or Early Iron Age are also well documented in colluvial deposits throughout European loess areas (Zolitschka et al. 2003, Dotterweich 2008, Lang 2003, Lang et al. 1999, Rommens et al. 2007). Although our chronological findings are based on only one profile, they confirm the hypothesis of early human land use and associated soil degradation and erosion with colluviation in the research area.

A maximum age for the younger colluvia can be derived from an archaeological site in the toeslope area near Venne (Rost & Wilbers-Rost 2011). At site Venne 2011 (Fig. 2), in the exemplary profile P1V1 a Holocene luvisol is developed on the loess material (Fig. 9). The upper part of this recent soil contains several archaeological findings of Late Iron Age to Roman origin. Replicate in-situ measurements of volume magnetic susceptibility in each soil horizon/sediment layer indicate high variances, most likely due to anthropogenic impact on the near-surface sediment at that time. These archaeological findings are buried by a 0.8 m thick colluvial layer. This colluvial layer is characterized by a homogeneous grain size distribution and increased LOI, indicating tilling activity during continuous deposition. The in-situ findings below this colluvial layer indicate a maximum age of 2 ka. However, since the highest values of soil erosion and colluviation in Germany are documented for late medieval times (Bork et al. 1998, Dotterweich 2003, Dotterweich 2008, Lang 2003), the colluvial deposits in this toe-slope position have to be considered as much younger. In their review work Bork & Lang (2003) show that average soil erosion at the upper and middle slopes was approximately 2.3 m for several sites in Germany since the Early Medieval period, whereas 80 % of that material was not transported out of the catchment areas but deposited on the lower slopes.

4.4 *Magnetic susceptibility of the soil horizons*

The findings in the profiles are supported by volume magnetic susceptibility of the different soil horizons are shown in the boxplots in Fig. 10. In general, the results of the magnetic susceptibility allow a good distinction of the different soil horizons:

High values were measured in the upper plough horizons (Ap), probably due to pedogenetic and bacterial enrichment of magnetite (Fassbinder et al. 1990). Lowest values were measured in the eluvial horizons (Al). Mean magnetic susceptibility of the colluvial layers (M) shows relatively low values as well, comparable to those of the Al-horizons. This indicates that the colluvial layers developed predominantly from eroded Al-material. As expected, the variance of the colluvial layers is extremely high. Bt-horizons show relatively high values comparable to those of the Cv-material, indicating in-situ soil formation. The weathered Jurassic parent material shows a high spatial variability, which is also reflected by the high variance of magnetic susceptibility values.

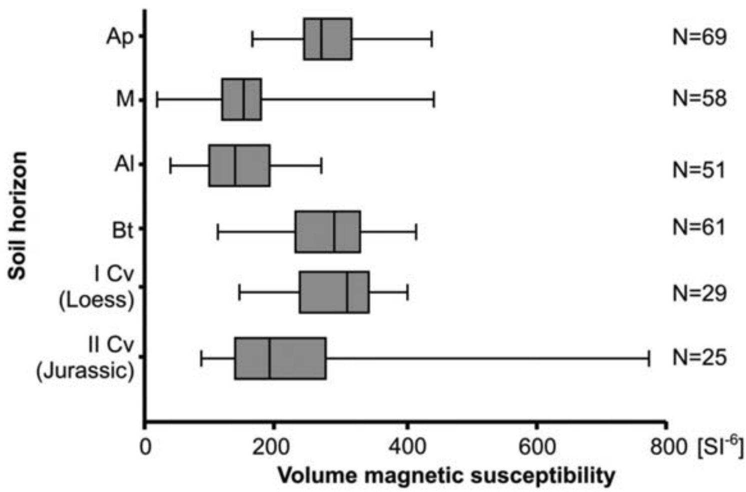

Fig. 10. Boxplots showing values of magnetic susceptibility for different types of soil horizons (positions of the various layers do not represent actual positions in the field).

4.5 *The landscape model*

The preliminary results of this study are compiled in Fig. 11 that shows the development of the landscape at Mount Kalkriese and the influence of human land use: A) During the Early and Middle Weichselian, ground moraine material of the Saalian glaciation and younger material were eroded by (geli)solifluction processes and accumulated in the valleys and at the toe-slopes. B) During the LGM, loess material was deposited on the hill slopes. Subsequently, the material was relocated over short distances probably during the Younger Dryas. C) During the Latest Pleistocene and the Early Holocene, pedogenetic processes lead to luvisol formation in the loess material. A clay illuviation horizon was formed at around 0.6 m below the surface. Since no indication of soil

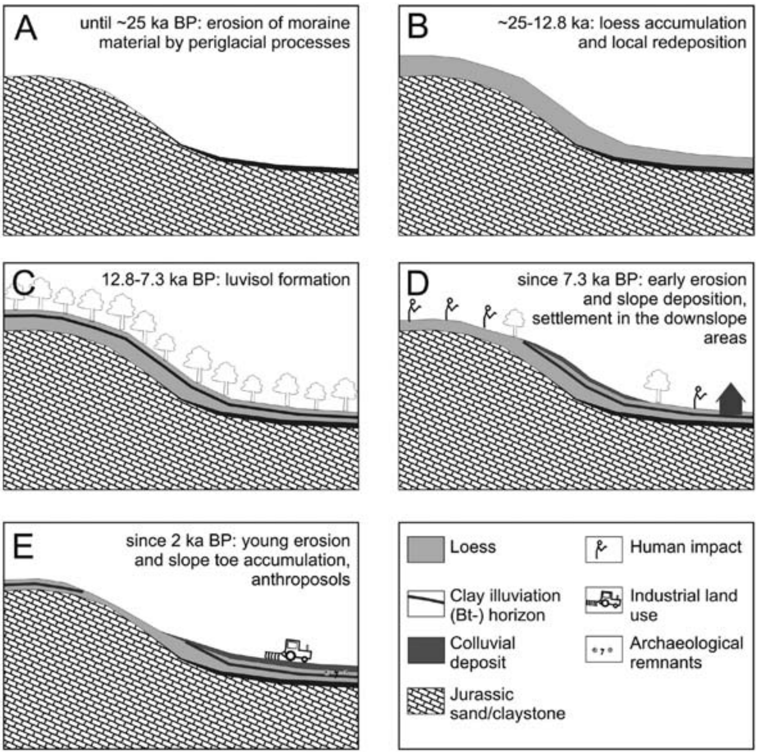

Fig. 11. Landscape evolution at Mount Kalkriese. A) Erosion of ground moraine (Saalian glaciation) and younger material by (geli)solifluction, accumulation in valleys and at the toe-slopes. B) Deposition of loess material on the hill slopes since the LGM and subsequently relocation over short-distances. C) Luvisol formation with no signs of soil erosion. D) Erosion in upslope areas as a result of human impact since the Late Mesolithic. Eroded material was stored in sediment traps on the slopes. At that time, human settlements existed in the downslope areas. E) Younger luvisol formation on eroded locations, leading to the modern weakly developed luvisols on the plateau. Concomitantly, slopes were subject to erosion processes. Increasing agricultural land use since the Medieval period resulted in relocation of older colluvia by tilling erosion. This material covered archaeological sites of Late Iron Age and Roman age. Locally, the loess cover was completely eroded.

erosion exists, a complete vegetation cover is assumed. D) Since about 7.3 ka (Late Mesolithic period), human impact possibly led to erosion of the luvisols in upslope areas. This erosion affected clay eluviation (Al) and (partly) clay illuviation (Bt) horizons. The eroded soil material was stored in sediment traps on the slopes. For that period human settlement is documented in downslope areas. E) Since about 2 ka, a secondary luvisol formation was initialized. This lead to the formation of the modern weakly developed luvisols on the plateau, whereas the slopes were subject to erosion processes. With the more intense agricultural land use since Medieval times, the older colluvial deposits were relocated downwards (tilling erosion). Today, they cover archaeological sites of Late Iron Age and Roman age. Locally, the loess is completely eroded.

5 *Conclusions*

Our study at Mount Kalkriese shows that onset and extent of human land use correspond well with with most colluvial archives from Central European loess regions: Soil erosion in the Wiehengebirge started at the Late Mesolithic-Early Neolithic boundary. For the Bronze Age, erosion and colluviation are documented by OSL datings as well. In agreement with numerous other studies, a considerable increase of soil erosion with correlated reworking of colluvial sediments was found since the Roman period, indicated by the burial of Germanic artefacts on the toe-slopes. However, further numerical datings in the research are necessary to verify our findings.

This study also shows typical problems when using the soilscape model for calculating the sediment budget: since truncated soil profiles are used for modeling eroded volumes, only minimum soil erosion is mapped. This leads to a huge discrepancy between eroded and accumulated volumes. Therefore, we have to assume that soil erosion in plateau and upslope areas was much higher than predicted by the soilscape model. In addition, it has to be assumed that extensive anthropogenic accumulation soils (Plaggen soils) were deposited in the downslope areas.

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