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Bw horizon in Holocene slope deposits (Kratzeburg, NE Germany) – dating and pedological characteristics

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Abstract: A soil-sediment sequence in NE Germany has provided information about the duration and intensity of formation of a Bw horizon in Holocene slope deposits. With a combination of optically stimulated luminescence (OSL), ^{14}C- and archaeological dating methods, colluvial layers taken from a former castle wall trench constructed during the Bronze Age were dated. With this chronology, the relative age of the postsedimentary Bw horizon formation within the colluvial sediments was derived, resulting in the first valid pedochronological data (maximum and minimum age) for a Holocene Bw horizon in NE Germany. The horizon was formed within 2400 years. Weathering and brunification have altered the Holocene parent material. However, the geochemical characteristics of the Holocene soil formation are weak compared to Bw horizons from the Late Glacial and the Late Glacial to Holocene. The results presented here enhance our understanding of soil formation processes in northern Germany, while highlighting the role of colluvial layers as sedimentological tracers of Holocene soil formation processes.

Bv-Horizont in holozänen Hangsedimenten (Kratzeburg, NO-Deutschland): Datierung und bodenkundliche Merkmale

Kurzfassung: Eine Boden-Sediment-Sequenz in Nordostdeutschland liefert Informationen zu Dauer und Intensität der Bodenbildung eines Bv-Horizontes in holozänen Hangsedimenten (Kolluvien). Mit einer Kombination aus optisch stimulierter Lumineszenz (OSL), ^{14}C- und archäologischen Datierungsmethoden werden Kolluvien in einem ehemaligen Burgwallgraben datiert, welcher während der Bronzezeit angelegt wurde. Mit Hilfe der Chronologie kann die in den kolluvialen Sedimenten stattgefundene postsedimentäre Bildung des Bv-Horizontes relativ datiert werden, womit für Nordostdeutschland erste gesicherte pedochronologische Daten (Maximal- und Minimalalter) für einen holozänen Bv-Horizont vorliegen. Der Horizont bildet sich innerhalb von 2400 Jahren. Verwitterung und Verbraunung führten zur Überprägung des holozänen Ausgangsgesteins. Die geochemischen Eigenschaften der holozänen Bodenbildung sind jedoch im Vergleich zu Bv-Horizonten aus dem Spätglazial und Spätglazial bis Holozän schwächer ausgeprägt. Die Ergebnisse vertiefen die Erkenntnis von Bodenbildungsprozessen in Norddeutschland, wobei die Rolle von Kolluvien als sedimentologische Tracer holozäner Bodenbildungsprozesse unterstrichen wird.

Keywords: *Bw horizon, Slope deposits, Holocene, soil formation, NE Germany, dating*

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1 Introduction

Colluvial layers are the result of soil erosion and reflect phases of Holocene human activity in the landscape (e.g., Bork et al. 1998, Dreibrodt et al. 2010). In contrast, soils developed within slope deposits indicate phases of subsequent stable land surfaces (e.g., Bork et al. 1998). Since unambiguous (genetic) evidence of Holocene parent material is required to identify Holocene soil formation, the precise dating of the parent material is crucial to obtain pedogenetic information about the timing, duration and characteristics of the postsedimentary soil formation (Semmel 1998).

Bw soil horizons are diagnostic horizons of in situ weathering (i.e. the recrystallisation of primary minerals of the parent material and the formation of new minerals) and brunification (e.g., Kuntze, Roeschmann & Schwerdtfeger 1994, Ad-hoc-AG Boden 2005, IUSS Working Group WRB 2006). These processes vary regionally and even locally in their timing, duration and intensity, due to different primary conditions of soil formation, such as climate, parent material and anthropogenic disturbances (e.g., Rehfuess 1990).

During archaeological investigations at a former fortified settlement close to the village of Kratzeburg in the Mecklenburg Lake District (NE Germany), Schubart (1961) described eroded material and soil horizons in a trench which was dug during the Bronze Age to protect the elevated settlement. As it contains a Bw horizon within a Holocene sequence, this soil-sediment sequence is of great

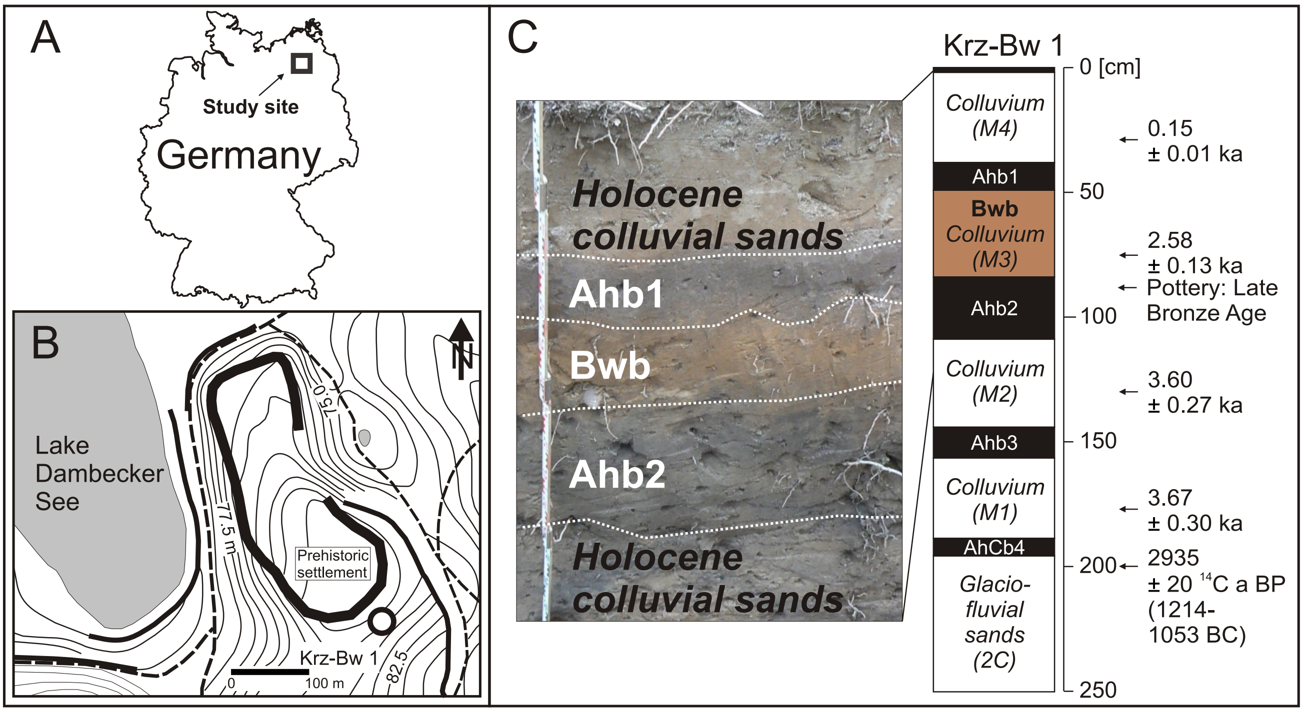

Fig. 1: Location of the study site (A). The investigated soil-sediment sequence is situated SE of the former Bronze Age fortified settlement (B). Simplified log of profile Krz-Bw 1 including datings and a photograph of the upper section showing the brownish Bw horizon developed in colluvium M3 (C).

Abb. 1: Lage des Untersuchungsgebietes (A). Die untersuchte Boden-Sediment-Sequenz befindet sich im Südosten der ehemaligen, während der Bronzezeit befestigten Siedlung (B). Vereinfachte Profilsäule des Profils Krz-Bw 1 mit Datierungen und Foto des oberen Abschnitts mit dem braunen Bv-Horizont im Kolluvium M3 entwickelt (C).

scientific interest: Firstly, dating the postsedimentary formation of the Bw horizon gives the first valid chronological data for Holocene Bw formation in NE Germany. Secondly, these ages can be compared with data from NW Germany. And thirdly, although few pedological and weathering parameters of Holocene Bw horizons have been described so far, such data are important to interpret the interaction of soil forming factors (e.g., climate, human impact) in different time slices (Late Glacial vs. Holocene) from a local to a regional perspective (e.g., Kaiser et al. 2009). A geochemical analysis at the Kratzeburg site will therefore provide data that characterize the Holocene formation of Bw horizons compared regionally to Late Glacial soils and soils formed since the Late Glacial.

2 Holocene Bw horizons in North Germany

Three sites with Holocene Bw horizons developed in colluvium have been identified in North Germany so far. Schmidtchen et al. (2003) describe a sequence of colluvial layers in Reddersknüll/Albersdorf (Schleswig-Holstein, NW Germany), where a Bw horizon developed between ca. 2800–1760 BC within the first colluvium covering Pleistocene parent material. At such pedostratigraphic positions, the unambiguous identification of an in situ weathered Bw horizon is difficult, partly because the colluvium may consist of allochthonous (eroded) Bw material from surrounding former autochthonous Bw horizons (e.g., Bussemer 1998).

A postsedimentary formation of a Bw horizon in Holocene sediments is described for NE Germany at the "Eldenaer Forst" site (Helbig et al. 2002). Here, a dating of organic rich sands below a Holocene colluvium indicates a maximum age for the soil formation of AD 80–420 (cal. ^{14}C). However, since there is no numerical dating of the colluvium itself, no minimum age is available.

Close to Glasow (Vorpommern, NE Germany), Schatz (2000) describes a postsedimentary Bw horizon and illuviation within a colluvium from the Pre-Roman Iron Age, covered by a second colluvium dated to the Early Middle Ages (Late Slavonic Period) by macroscopical and pedostratigraphic interpretation. The Holocene soil formation process is claimed to even affect the underlying autochthonous glaciofluvial Pleistocene sands down to 1.3 m depth.

3 Study site and methodology

3.1 Study site

Located in NE Germany within the headwaters of the Havel river, the relief of the area of the study site is dominated by moraines of the Pomeranian ice-marginal zone of the Weichselian glaciation (ca. 20 ka, Lüthgens & Böse 2011). There are several lake and peat depressions adjacent to outwash plains, which were partly reshaped by human-induced erosional processes during the Bronze Age, the Medieval and the Modern Era (e.g., Küster & Preusser 2009, Küster et al. 2012, Küster et al. 2014). The area is situated in a transition zone from maritime to continental climate, with an annual precipitation of 570–580 mm (e.g., Kaiser & Zimmermann 1997). Today, the area is mostly covered by pine forest. The investigated profile Krz-Bw 1 is located at the foot of a slope of a sandy moraine within

Tab. 1: Sedimentological parameters of profile Krz-Bw 1.

Tab. 1: Sedimentologische Parameter des Profils Krz-Bw 1.

Soil horizon	Colluvium	Depth	Color	pH	LOI	Clay	Silt	F.-Sand	M.-Sand	C.-Sand
		[cm]	[Munsell]		[%]	[%]	[%]	[%]	[%]	[%]
Ah	M4	2	10YR 2/1	-	-	-	-	-	-	-
C	M4	40	10YR 4/2	3.95	0.69	0.85	2.26	21.77	59.41	15.71
Ahb1	M3	50	10YR 3/2	4.06	1.01	0.56	2.28	13.95	56.20	27.01
Bwb	**M3**	**80**	**10YR 4/6**	**4.07**	**0.68**	**0.43**	**1.07**	**6.61**	**55.24**	**36.65**
Ahb2	M2	110	10YR 3/1	4.83	0.68	0.42	0.84	8.96	57.77	32.01
C	M2	145	2.5Y 4/2	5.33	0.51	0.49	1.41	10.72	57.91	29.47
Ahb3	M1	155	10YR 3/1	5.35	0.55	0.41	1.14	8.27	58.30	31.88
C	M1	180	2.5Y 4/2	5.37	0.62	0.44	0.66	11.58	59.96	27.36
AhCb4	-	195	10YR 3/1	5.47	0.65	0.49	1.29	12.62	58.89	26.71
2C	-	250	2.5YR 7/2	6.18	0.37	0.43	0.37	11.95	65.93	21.32

Tab. 2: Major elements and chemical weathering indices of selected horizons of profile Krz-Bw 1.

Tab.2: Hauptelemente und chemische Verwitterungsindizes von ausgewählten Horizonten des Profils Krz-Bw 1.

Horizon	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	TiO_2	Ruxton (1968)	Kronberg & Nesbitt (1981)		Harnois (1988)
	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	SiO_2/Al_2O_3	Ordinate	Abscissa	CIW
C	77.43	2.91	0.72	0.04	0.19	0.27	0.67	1.02	0.08	0.20	45.14	0.48	0.98	64.74
Ahb1	88.84	3.48	0.79	0.11	0.19	0.29	1.00	1.18	0.09	0.19	43.26	0.50	0.98	61.60
Bwb	**90.95**	**3.56**	**0.75**	**0.03**	**0.20**	**0.30**	**0.67**	**1.15**	**0.08**	**0.17**	**43.32**	**0.45**	**0.98**	**68.46**
Ahb2	91.08	3.33	0.72	0.03	0.21	0.33	0.70	1.11	0.06	0.15	46.43	0.47	0.98	65.51
C	88.33	3.65	1.01	0.06	0.25	0.45	0.65	1.19	0.11	0.22	41.01	0.47	0.98	65.88

Tab. 3: OSL ages and dosimetry data of profile Krz-Bw 1. Based on the palaeodose characteristics (overdispersion and skewness), either the Central Age Model (CAM) or the Minimum Age Model (MAM-3) acc. to Galbraith et al. (1999) was applied. OD = overdispersion. Statistical values and age models were calculated in R (luminescence package 0.4.2).

Tab. 3: OSL-Alter und Dosimetrie-Daten des Profils Krz-Bw 1. Unter Berücksichtigung der Paläodosis-Eigenschaften (Überstreuung und Schiefe) wurde entweder das Central Age Model (CAM) oder das Minimum Age Model (MAM-3) nach Galbraith et al. (1999) angewandt. OD = Überstreuung. Statistische Kenngrößen und Altersmodelle wurden in R berechnet (luminescence package 0.4.2).

Lab. No.	Depth	U	Th	K	Cosmic dose rate	Water content, measured	Water content, estimated	Dose rate	Palaeodose characteristics		Palaeodose		OSL age	OSL age
	[m]	[ppm]	[ppm]	[%]	[Gy/ka]	[%]	[%]	[Gy/ka]	OD [%]	Skew	Age Model	[Gy]	[ka]	[a AD/BC]
HUB-0183	0.30	0.80 ± 0.09	2.75 ± 0.32	1.18 ± 0.03	0.21 ± 0.01	7.5	8 ± 3	1.62 ± 0.07	1.5 ± 1.2	0.25	CAM	0.24 ± 0.01	0.15 ± 0.01	AD 1860 ± 10
HUB-0184	0.76	1.03 ± 0.08	3.16 ± 0.18	1.17 ± 0.03	0.20 ± 0.01	9.5	10 ± 3	1.63 ± 0.07	10.3 ± 0.8	0.2	CAM	4.21 ± 0.13	2.58 ± 0.13	570 ± 130 BC
HUB-0185	1.30	1.24 ± 0.08	4.23 ± 0.25	1.41 ± 0.03	0.19 ± 0.01	12.3	12 ± 3	1.90 ± 0.08	28.9 ± 2.2	1.11	MAM-3	6.84 ± 0.43	3.60 ± 0.27	1590 ± 270 BC
HUB-0186	1.74	1.16 ± 0.09	3.54 ± 0.26	1.28 ± 0.03	0.19 ± 0.01	10.1	10 ± 3	1.77 ± 0.07	34.2 ± 2.7	1.25	MAM-3	6.50 ± 0.46	3.67 ± 0.30	1660 ± 300 BC

the ice-marginal zone, close to the village of Kratzeburg. During the Bronze Age, there was a fortified settlement on top of the moraine, surrounded by a trench, which was recently filled with colluvial sediments (Schubart 1961; Fig. 1).

3.2 Field methods

For sedimentological work and dating purposes, a soil profile was dug into the trench, which was then described following the guidelines of the German soil survey (Ad-hoc-AG Boden 2005, "KA 5"). The soil horizons were classified according to the IUSS Working Group WRB (2006), with the one difference that colluvial layers were designated following Dreibrodt & Bork (2005; see Fig. 1): i.e., with "M" and a number representing the order of accumulation ("M1" first, "M2" second, etc.). To document pedological parameters and to explain any changes in pedogenetic processes, standard soil parameters were determined. Colours of soil horizons were determined according to Munsell (1994).

3.3 Laboratory methods

The grain size distribution of the profile was determined by laser diffractometry of fine sediments. The organic matter content was estimated by loss on ignition (LOI) at 550 °C for two hours after crushing and drying each sample. The soil pH was determined potentiometrically in 0.01 M $CaCl_2$ (see Table1), while the soil element concentrations were measured using a Philips PW 2404 RFA-spectrometer. The weathering indices (Table 2) were calculated based on the element molar ratios following Ruxton (1968) and Harnois (1988). To compare weathering quantities from different study sites in NE Germany, Kronberg & Nesbitt (1981) was used (e.g., see method in Bussemer 1999, Bussemer 2005 and Küster & Preusser 2009).

3.4 Chronology

To obtain a consistent and valid chronology of soil-sediment sequences, a variety of dating methods should be

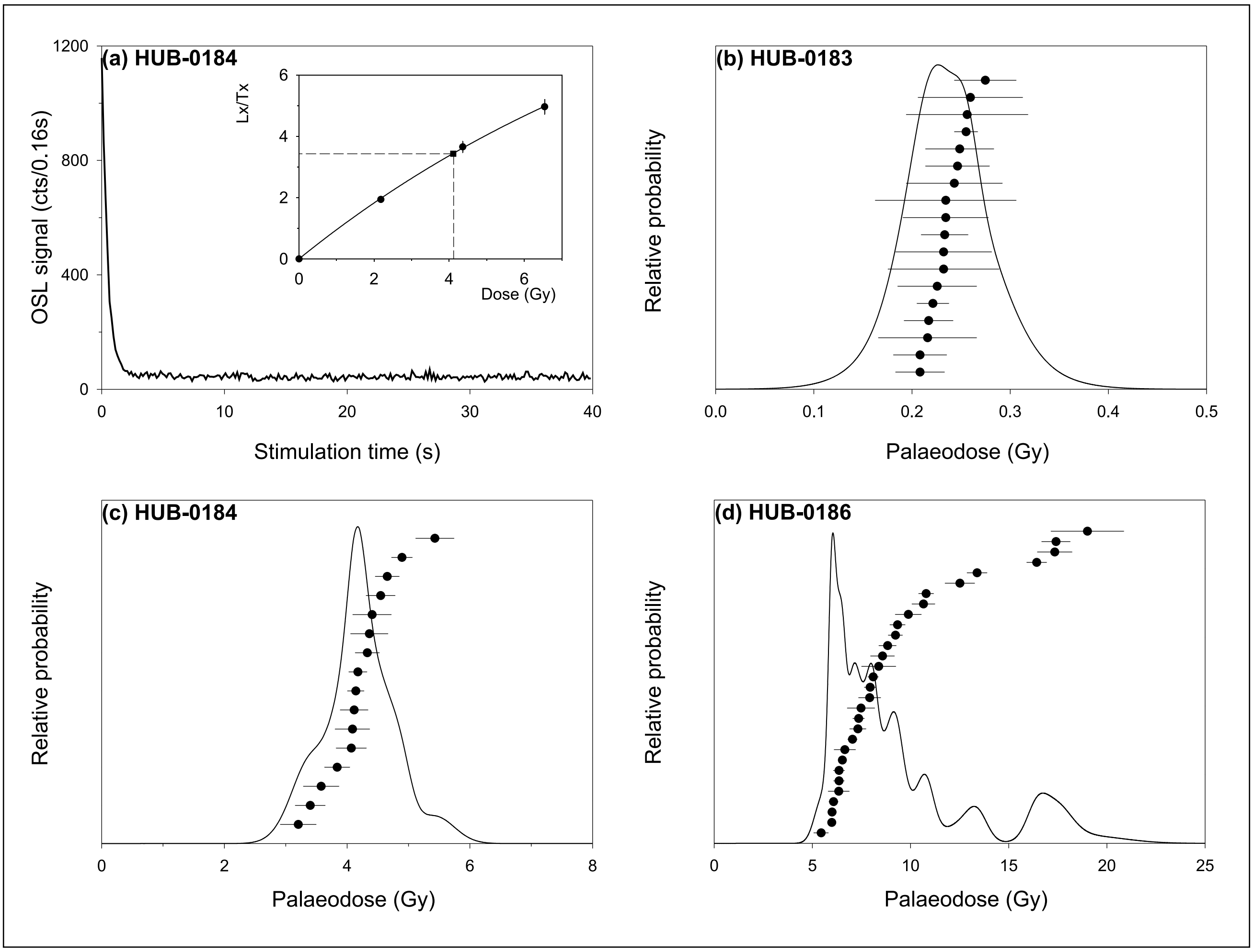

Fig. 2: Typical OSL shine down curve with fast decaying quartz OSL signal and dose response curve (Lx/Tx = test dose corrected OSL signal) (a). Palaeodose plots with probability density functions of HUB-0186 (colluvium M1), HUB-0184 (M3), and HUB-0183 (M4) (b–d). HUB-0183 and HUB-0184 show narrow palaeodose distributions (b, c), HUB-0186 and HUB-0185 (not displayed) yielded positively skewed multimodal palaeodose distributions, most likely indicating insufficient resetting of the OSL signal before burial, possibly leading to an age overestimation.

Abb. 2: Typische OSL-Ausleuchtkurve mit schnell zerfallendem Quarz-OSL-Signal und Dosisfunktion (Lx/Tx = testdosiskorrigiertes OSL-Signal) (a). Paläodosis-Einzelwerte mit Wahrscheinlichkeitsdichtefunktionen von HUB-0186 (Kolluvium M1), HUB-0184 (M3) und HUB-0183 (M4) (b–d). HUB-0183 und HUB-0184 zeigen enge Paläodosisverteilungen. HUB-0186 und HUB-0185 (nicht dargestellt) ergaben rechtsschiefe, multimodale Paläodosisverteilungen, die als Zeichen unvollständiger OSL-Signalrückstellung während der Kolluviation gewertet werden und deshalb zu einer Altersüberschätzung führen können.

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used, depending on the available datable material (e.g., Niller 1998, Dreibrodt & Bork 2005). Because of the presence of archaeological finds (pottery), organic material (bones) and clearly detectable colluvial units, three different dating methods could be used: archaeological, radiocarbon and luminescence. For radiocarbon dating, a sample was taken from a bone of a bovine skeleton found at ca. 2 m depth (sample KIA 45553) (calibration with CALIB 5.0.1, Stuiver & Reimer 1993, Stuiver, Reimer & Reimer 2005). Optically stimulated luminescence (OSL) samples were collected from undisturbed Holocene parent material (colluvial layer) not penetrated by roots from above. OSL ages (Table 3) were measured using the sand sized quartz fraction (90–200 µm) using the single-aliquot (SAR) protocol from Murray & Wintle (2000). The palaeodoses were measured on a Risø TL-DA 15 luminescence reader. Small aliquots (2 mm) were used, containing ca. 200 grains each; the preheat temperature was set to 180 °C (10 s), and the test dose cutheat temperature to 160 °C. The dose rates were provided by gamma ray spectroscopy (Ortec HPGe detector).

4 Results

The base of profile Krz-Bw 1 consists of glaciofluvial sand, which is traced at its top by a partly reworked surface horizon displayed by the higher LOI (AhCb4, Fig. 1, Table 1). The bovine skeleton is situated just below the organic horizon. The Holocene sedimentation is represented by four colluvial layers (M1–M4). Within the basal colluvial layer M1, a surface horizon is visible (Ahb3). In colluvium M2, a surface horizon can be recognized with pottery fragments at the top, typical for the Late Bronze Age in Northern Germany. In both colluvial layers M1 and M2, small iron-manganese bands (ca. 1 mm thick) are visible. From colluvium M2 to colluvium M3, a shift of pH values was identified, indicating a change from strong to moderate soil acidity (Table 1). Colluvium M3 is pedologically characterized by a brownish (10YR 4/6) Bw horizon and a humic surface horizon (Ahb1). The fourth colluvium M4 appears at the top of the sequence, with the recent thin surface horizon (Ah).

The calculated weathering indices, especially the indices from Kronberg & Nesbitt (1981) and Harnois (1988), identify the Bw horizon as the main weathering zone in the profile (Table 2). However, no high amount of fine grain sizes such as clay is recognisable as a possible result of weathering (e.g., Bussemer 2005, Table 1). Based on the geochemical results and the macroscopic features, this horizon can be classified as a typical Bw horizon for NE Germany (see e.g., Schlaak 1993, Bussemer 2005, Bussemer, Schlaak & Gärtner 2009, Küster & Preusser 2009). Because the Bw horizon is almost identical with the colluvial (parent) material, there are no data available from the parent material itself of colluvium M3 that can be compared to the (postsedimentary modified) Bw material.

The bone of the bovine skeleton found at the base of the profile was ^{14}C dated to 2935 ± 20 a BP (1214–1053 BC, KIA 45553). The M1 colluvium was OSL dated to 3.67 ± 0.30 ka (HUB-186, Table 3), while colluvium M2 had an OSL age of 3.60 ± 0.27 ka (HUB-185). The highly scattered and positively skewed palaeodose distributions of these two OSL samples (Table 3; Fig. 2) suggest an insufficient resetting of the luminescence signal during the last sedimentation, which is typical for colluvial sediments. To avoid an OSL age overestimation and to get as close as possible to the true sedimentation ages, the Minimal Age Model (MAM-3, three-parametric Minimum Age Model) of Galbraith et al. (1999) was applied, which gives more weight to the low palaeodoses (sigma b = 0.1, based on the overdispersion of samples HUB-0183 and HUB-0184). The OSL age of colluvium M3 is 2.58 ± 0.13 ka (HUB-184), which agrees with the archaeological dating of the Late Bronze Age pottery. OSL sample HUB-183 dates the accumulation of the uppermost colluvium M4 to 0.15 ± 0.01 ka. The reliability of the upper OSL datings M3 and M4 is confirmed by good luminescence properties and narrow normal palaeodose distributions, indicating complete bleaching of the OSL signal during the last sedimentation cycle (Fig. 2). To calculate the palaeodoses, the Central Age Model (CAM) (Galbraith et al. 1999) was used. Gamma ray spectroscopy did not reveal any evidence for a radioactive disequilibrium in all OSL-dated sediment samples.

5 Discussion

To date the soil-sediment sequence, a combination of OSL and ^{14}C dating methods, and archaeological finds was used. While the ^{14}C dates give a maximum age for the Holocene sedimentation, the OSL ages provide the absolute time of the accumulation of the colluvial layers. The time periods between the colluvial sedimentations are characterized by soil formation within the colluviums. The timing of the soil formation can be derived from the maximum age of the parent material and the minimum age of the colluvium above. Considering the deposition ages of colluviums M3 and M4, respectively 570 ± 130 BC and AD 1860 ± 10, the formation of the horizon Ahb1 and Bwb took place during a period of about 2400 years (Bronze Age-Modern Times). The age of colluvium M3 is supported by the pottery, which is typical for the Late Bronze Age. The periods of soil formation between sedimentation of the colluvial layers M1–M3 and the period between accumulation of M4 until today are shorter than between accumulation of M3 and M4. Only humic surface horizons have formed in the parent materials.

The weathering indices indicate that the Bw horizon is the main weathering zone in the investigated profile. Due to the fact that the soil horizon occupied virtually the entire colluvium, a separate geochemical analysis was not possible, and neither could the weathering indices of the soil and parent material be calculated. As the upper colluvium M4 contains relocated brownish soil material, the Bw horizon could have formed along the slope up to the slope shoulder before being incorporated into the colluvial sediments currently covering the Bw horizon at location Krz-Bw 1, during the erosional processes of the Modern Era. Thus, there is also pedogeomorphic evidence for in situ soil formation of the investigated Bw horizon.

The comparison with other Bw horizons that have developed in sandy substrates in NE Germany, using the weathering indices and theoretical weathering path of rocks proposed by Kronberg & Nesbitt (1981), suggests a lower degree of weathering of the Holocene soil horizon at the Kratzeburg site, not reaching the levels of the

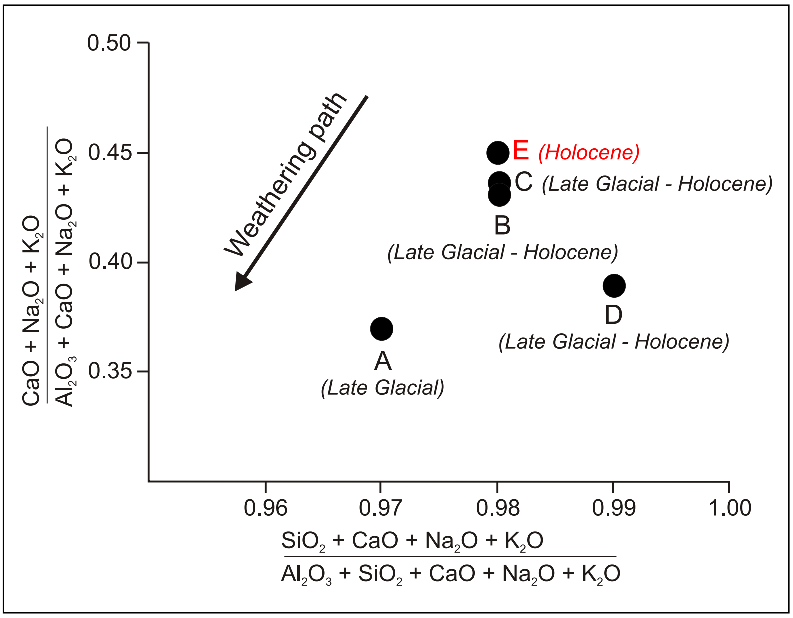

Fig. 3: Comparison of weathering indices (Kronberg & Nesbitt 1981) from Bw horizons in NE Germany; (A) Late Glacial Bw horizon ("Finow soil") from Blankenförde (Küster & Preusser 2009); (B) Late Glacial – Holocene Bw horizon from Blankenförde (Küster & Preusser 2009); (C) Late Glacial – Holocene Bw horizon from the Hirschfelder Heide (Bussemer 2005); (D) Late Glacial – Holocene Bw horizon from Prötzel (Bussemer 1999); (E) Holocene Bw Horizon (red) from Kratzeburg (this study). The theoretical weathering path according to Kronberg & Nesbitt (1981) is shown by the arrow.

Abb. 3: Vergleich der Verwitterungsindizes (Kronberg & Nesbitt 1981) von Bv-Horizonten in Nordostdeutschland; (A) Spätglazialer Bv-Horizont („Finowboden") aus Blankenförde (Küster & Preusser 2009), (B) Spätglazial-holozäner Bv-Horizont aus Blankenförde (Küster & Preusser 2009), (C) Spätglazial-holozäner Bv-Horizont aus der Hirschfelder Heide (Bussemer 2005), (D) Spätglazial-holozäner Bv-Horizont aus Prötzel (Bussemer 1999), (E) holozäner Bv-Horizont (rot) aus Kratzeburg (diese Studie). Der theoretische Verwitterungspfad nach Kronberg & Nesbitt (1981) wird mit dem Pfeil gezeigt.

Late Glacial and Late Glacial to Holocene horizons (e.g., Bussemer 1999, Bussemer 2005, Küster & Preusser 2009, Fig. 3). However, the brownish colour of the Kratzeburg Bw horizon corresponds with horizons in other profiles in the region (see Munsell 1994). At the Kratzeburg site, brunification seems more likely to have contributed to the soil Bw formation than weathering has. The occurrence of Fe and Mn bands below the Bw horizon signals increasing pH values, as well as slight gleyification.

6 Conclusions

Numerical (OSL and ^{14}C) and relative (archaeological finds) datings of the soil-sediment sequence at Kratzeburg (NE Germany) could delimit the duration needed to form the Bw horizon developed in a Holocene colluvial layer. At the Kratzeburg site, the Bw horizon formed within a period of at least 2400 years, lasting from the Late Bronze Age to the Modern Era. So far, the Kratzeburg and Reddersknüll/Albersdorf (see chapter 2) sites are the only two pedostratigraphic soil-sediment sequences that have been evaluated with maximum and minimum ages in Northern Germany. They indicate a period of Bw formation in Holocene colluvial parent material between 1000 and 2400 years. A comparison of weathering parameters suggests a lower degree of weathering of the Holocene Bw horizon at Kratzeburg compared to Bw horizons from the Late Glacial and Late Glacial to Holocene in NE Germany.

It is hoped that these results, rather than giving final conclusions, will revive the discussion of Holocene Bw formation. More profiles with Bw horizons with adequate chronologies and comparable geochemical analyses are desirable for future soil geographic and genetic interpretations.

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