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Spring fed raised peat hummocks with tufa deposits at the Farbeberg hills (Northwest-Germany): Structure, genesis and paleoclimatic conclusions (Eemian, Holocene)

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Abstract: Spring fed raised calcareous peat hummocks in Schleswig-Holstein (Northwest-Germany) were investigated by means of geological methods, pollen analysis and ^{14}C-dates. Artesian water discharges locally cause the growth of hills and ridges consisting of peat, organic / calcareous mud and tufa. Spring discharges at the Northern Farbeberg hill (near Hohenwestedt) are active since at least the beginning of the Eemian. Eemian interglacial deposits with a thickness of more than 7 m are built from massive tufa and yellow lacustrine sequences with varve-like layering. Eemian pollen from zones E-I, E-II, E III, E-IVa, b, and E-VII according to Menke & Tynni (1984) were found. The Eemian deposits occur together in superposition with Holocene carbonate sediments intercalated in peat. Pollen analysis shows Preboreal, Boreal, Atlantic period and Subboreal at the southern Farbeberg; Meiendorf-Interstadial, Preboreal, Boreal, Atlantic period and Subboreal at the northern Farbeberg. Intercalated carbonate deposits indicate a tufa formation also during the Weichselian interstadials, which harmonizes with the idea of a continuously existing talik. Despite unreliably high ^{14}C-ages of the carbonates these generally are in accordance with the pollen age indications. The younger tufa precipitation at the Farbeberg hills begins in the Weichselian Lateglacial and ends in the Preboreal (12,520 until 10,750 cal a BP, southern Farbeberg) at the boundary Boreal / Atlantic (12.520 ^{14}C cal a BP until 8.354 ^{14}C cal a BP, northern Farbeberg). The data indicate an enhanced decalcification of the near-surface sediments in the Lateglacial / Early Holocene and preferred tufa deposition occurring during the climatic optimum phases from Preboreal to Atlantic period.

Quellmoor-Kuppen mit Sinterkalk-Bildungen der Farbeberge (Nordwest-Deutschland): Aufbau, Genese und paläoklimatische Aussagen (Eem-Warmzeit, Holozän)

Kurzfassung: Quellkalkmoor-Hügel in Schleswig-Holstein wurden mittels geologischer Methoden, Pollen- und ^{14}C-Datierungen untersucht. Quellaustritte gespannten Grundwassers führen örtlich zur Bildung von morphologischen Kuppen und Wällen aus Torf, Organik- und Kalk-Mudde sowie Quellkalk. Quellschüttungen am nördlichen Farbeberg sind spätestens seit dem Beginn der Eem-Warmzeit aktiv. Hier treten bis zu 7 m mächtige Eem-warmzeitliche Ablagerungen in Form von massiven Kalksinterbildungen und gelben limnischen Sequenzen, teilweise mit Warven-artiger Schichtung auf. Es wurden die Eem-Pollenzonen E-I, E-II, E III, E-IVa, b, and E-VII nach Menke & Tynni (1984) nachgewiesen. Die Quellablagerungen der Eem-Warmzeit finden sich zusammen mit vergleichbaren Ablagerungen des Holozäns in Superposition. Die Pollenanalyse zeigt Präboreal, Boreal, Atlantikum und Subboreal am südlichen Farbeberg, sowie Meiendorf-Interstadial, Präboreal, Boreal, Atlantikum und Subboreal am nördlichen Farbeberg. Zwischengeschaltete Kalkbildungen in den Weichsel-Ablagerungen weisen auf eine Quellkalk-Sedimentation auch während der Weichsel-Interstadiale hin, was mit der Vorstellung eines kontinuierlich existierenden Taliks im Quellbereich harmoniert. Trotz der hohen ^{14}C-Alter der Kalke ist eine generelle Übereinstimmung mit den Pollendatierungen vorhanden. Die jüngere Kalkausfällung an den Farbebergen beginnt im Weichsel-Spätglazial und reicht bis in das Präboreal (12,520 until 10,750 cal a BP, südl. Farbeberg), bzw. an die Grenze Boreal / Atlantikum (12.520 bis 8.354 ^{14}C a BP, nördl. Farbeberg). Es wird von einer Kombination aus zeitlich begrenzter, verstärkter Entkalkung der oberflächennahen Sedimente im Spätglazial / Frühholozän und klimatisch bevorzugter Kalkausfällung während der Wärmeoptima von Präboreal bis Atlantikum ausgegangen.

Keywords: spring mire, locally elevated calcareous bogs, climate change, Eemian, late Holocene tufa decline, paleohydrogeology

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1. Introduction

Spring fed raised peat hummocks in valleys and bogs of Schleswig-Holstein (Northern Germany) are primarily hydrogeological phenomena associated with the localized more or less vertical entry of confined groundwater or lateral flowing groundwater to the near surface geosphere (Grube & Usinger 2016). Due to the special hydrological conditions and the corresponding nutrient and pH-conditions found at these sites often a rare flora and fauna exists (Martin & Brunke 2012). At such locations, in addition to the most dominant limnic-telmatic sedimentation, deposition of calcareous deposits occurs in the form of massive tufa. This paper is addressed to the spring fed raised peat hummocks of the "Farbeberge" in the area of the stream of the Rüterbek near Nindorf / Hohenwestedt (fig. 1). The term "Farbeberg" means "color hummock" and refers to the digging of calcium carbonate used in the production of color in former times. While the southern Farbeberg is mentioned in the literature (Petersen 1892), the northern Farbeberg was "discovered" during the investigations and examined in greater detail. The latter is of particular importance for the objective of this work. Additionally spring fed raised calcareous peat hummocks in Habernis (Flensburg Fjord) and Curau (near Ahrensbök, Ostholstein; Grube & Usinger, 2016) are discussed. The objectives of this study are to explore the structure and stratigraphic position of the Farbeberge, regarding the genesis of the structures, taking into account the groundwater conditions and the paleoclimatic conditions. The intention is to consider whether the (late) Holocene tufa decline (Goudie, Viles & Pentecost 1993, Pentecost 2005) described elsewhere, can also be found in Northern Germany. This trend is supposed to apply to older interglacials also (Lozek 1965). This is raising the question whether this lack of "replenishment" of calcium carbonate is because of decalcification of near-surface sediment, variable temperature-pressure conditions or changing conditions in the aquifer. Comparison of the carbonate sediments of the Eemian with those of the Holocene – both occur in superposition at the site northern Farbeberg – permits a new study of the processes of formation of tufa sediments.

2. Formation of tufa and spring fed peat / tufa hummocks

There exists a manifold of terms to describe calcareous spring deposits in Germany. The term "Kalktuff"„ (Groschopf 1969) is frequently used. According to Hinze et al. (1989) "Kalktuff„ is referred to as "cellular-porous unconsolidated and/or solid rock, mainly calcite, rarely aragonite, usually with imprints of plants (leaves, stems) and remains of snails, mussels etc.". Here we use the international term "tufa" for solid, limestone-like material; and "calcareous mud" for softer calcareous sediment. The precipitation of calcareous sediments is mainly dependent on the carbon dioxide content of water, key factors are increasing the temperature and a reduction of pressure (Heykes 1931, Jäger & Ložek 1968, Groschopf 1969, Bakalowicz 1990). The photosynthetic activity (CO_2 extraction by algae and other plants) and the built-in calcareous shells of snails, etc. may also play a greater role. Calcite dominates over aragonite as main mineral phase. Generally, calcareous precipitates in peat are limited to small horizons (Moore & Bellamy 1974); massive limestones (tufa) in contrast are rare. The calcium carbonate precipitation is expected to form mainly subaerially. However, according to Sendtner (1854) the formation of "Wiesenkalk" takes place below peats by dissolving snail and mollusc shells by humic acids and subsequent deposition of calcium carbonate under the influence of oxygen-rich groundwater. The opposite is the re-dissolution of limestones by oxidation. Decalcification of the layers during the Holocene is e. g. described by von Vreeken (1981), lower temperatures lead to an increased resolution of carbonate sediments.

To date, little information exists about the absolute ages of calcareous spring deposits in Central Europe. Dobrowolski, Durakiewicz & Pazdur (2002) examined spring fed calcareous hummocks in eastern Poland. Their studies, based on isotope analyses (^{14}C, ^{18}O), showed preferred phases of calcium carbonate precipitation at 10.3 to 9.9; 8.0 to 7.5; 6.7 to 6.5; 6.0 to 5.6; 2.5 to 1.7 and 1.0 to 0.6 ka BP. These periods correspond with relatively warm and rainy phases of the Holocene. Pazur et al. (2002) suggest that the main stage of formation was during the climatic optimum around 5.0 to 6.0 ka B.P. Jäger & Lozek (1968) found a more continuous formation of limestone mostly in the Atlantic / Subatlantic period, after that a discontinuous formation is observed. The beginning of carbonate formation is given here as to be the Preboreal. Laumets, Kalm & Zohar (2010) provide a comparison of different research findings: the main phase of tufa formation is summarized with 9.4 to 7.4 ka BP. The reasons for changing Holocene calcium carbonate precipitation are discussed. In summary, most authors believe in climate-controlled calcium carbonate sedimentation, a corresponding exchange between carbonatic and telmatic sedimentation, or rising groundwater temperatures (Schuster 1926, Goudie et al., Vreeken 1981, Almendinger & Leete 1998, Dramis, Materazzi & Cilla 1999).

The hydrogeological conditions required for the formation of spring fed peat/calcareous hummocks are discussed in various studies. The concepts include sites characterized by glacigenic soft sediments, such as glacilimnic sediments, underlain by confined aquifers, that are locally penetrated (by features such as sand banks or veins). Examples are given for the Midwest USA (Ciolkosz 1965, Wilcox, Shedlock & Hendrickson1986, Thompson & Bettis 1994, Carpenter 1995, Amon et al. 2002, Glaser et al. 1997). Water budgets for such sites are extremely complex and descriptions of such are largely absent (Carpenter 1995).

3. Existing knowledge about tufa formation with focus on Northern Germany

Quaternary carbonate precipitation in northern Germany is usually formed in lacustrine environments (Geinitz 1920, Thienemann 1922, Lenz 1924, Schuster 1926, Mende 1956, Strehl 2001, Dörfler et al. 2012). Extensive, thick carbonate sediments typically occur as fine lacustrine detritus calcareous muds partially filling larger depressions. These do not lead to morphological forms such as hummocks on slopes. Typically, carbonates in bogs are most often found in areas with underlying massive limestones, such as the "Thüringer Muschelkalk" area, the chalk on the Rügen island, chalk deposits in East Anglia, Canada and the USA (Succow & Joosten 2001, Paulson 2001, Gilvear et al. 1993, Vreeken 1981, Amon et al. 2002). Alaily et al. (2001) describe tufa from the area Tegel Creek / Blankenfelde, that are very young and occur small scaled and shallow. Spring fed calcareous bogs are a widespread phenomenon in North-West Germany. According to Raabe (1980) these in Schleswig-Holstein occur main-

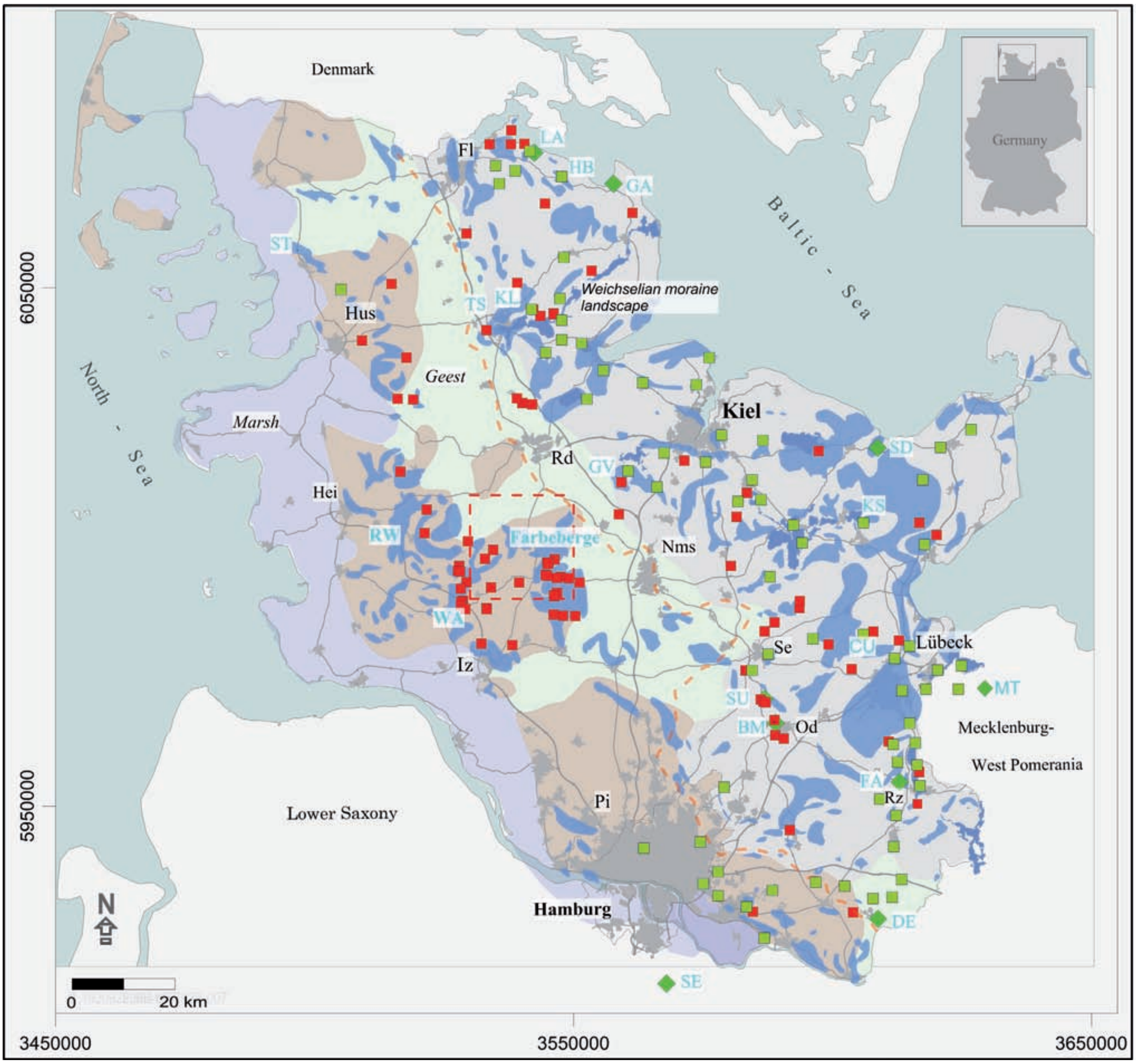

Fig. 1: Occurrence of locally elevated bog spring areas (red; according to Biotope Register Schleswig-Holstein / LLUR SH, supplemented by own survey), calcareous spring mires (green) according to Raabe *(1980), position of wider investigation area (fig. 2, with red dashed line) in front of glacitectonically influenced areas (blue, according to* Stephan *2004, modified by authors). LGM shown with dashed orange line. Abbr.: CU=Curau, BM=Brenner Moor, DE=Delvenau, FA=Farchau, FB=Farbeberge, GA=Geltinger Au, GV=Groß Vollstedt, HB=Habernis, KS=Kellersee, Kl=Klensby, LA=Langballigau, MT=Maurinetal, Ri=Riesewohld, SD=Sechendorf, ST=Seevetal, SÜ=Sühlen, TS=Tiergarten Schleswig, St=Stollberg, Wa=Wacken.*

Abb. 1: Vorkommen von Quellbereichen mit Kuppen-förmiger Ausbildung (rot; nach Biotopkataster Schleswig-Holstein / LLUR SH, ergänzt durch eigene Aufnahmen) und Kalkquellmooren (grün) nach Raabe *(1980), Lage des weiteren Untersuchungsgebietes (Abb. 2, rot gestrichelt) vor dem Hintergrund glazitektonischer Stauchungen (blau, nach* Stephan *2004, ergänzt durch Autoren). Maximale Ausdehnung der Weichsel-Kaltzeit orange gestrichelt dargestellt. Abkürzungen: CU=Curau, BM=Brenner Moor, DE=Delvenau, FA=Farchau, FB=Farbeberge, GA=Geltinger Au, GV=Groß Vollstedt, HB=Habernis, KS=Kellersee, Kl=Klensby, LA=Langballigau, MT=Maurinetal, Ri=Riesewohld, SD=Sechendorf, ST=Seevetal, SÜ=Sühlen, TS=Tiergarten Schleswig, St=Stollberg, Wa=Wacken.*

ly in the eastern hill country (Weichselian moraine landscape; fig. 1). Thienemann (1922) describes the combined occurrence of tufa and calcareous muds. Gripp (1964) lists several spring fed bogs on slopes (Farbeberg at Nindorf, Farchau, Sechendorf, Sühlen).

In the presence of calcium-rich ground waters, morphologically prominent forms can be formed in soft rock areas with Pleistocene sediments, such as till. Spring-fed raised calcareous peat hummocks and other morphological landscape forms containing tufa, have variously been described in the literature from North Germany, and North / Central European region (Weber 1907, Keilhack 1928, von Bülow 1929, Jäger 1966, Kirchner 1971, Succow 1988). Weber (1907) mentions small-scale spring fed raised peat hummocks with calcareous layers frequently occurring in the end moraine areas of Northern Germany. Kirchner (1975) investigated small peat hummocks fed by artesian ground waters in the sandy, today swampy floodplains as exfiltration areas – he mentions the following identifying features: The presence of tufa, a strong peat decomposition, an increased incidence of iron precipitates or ocher as well as the specific type of soil wetness.

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Tüxen (1985a, b) reports on peat hummocks and peat walls from Lower Saxony (see also Tüxen 1990). Bremer (1996) describes numerous watch glass formed calcareous spring bogs from the area of the Maurine Valley (Schönberg, Mecklenburg-Vorpommern), which have a height of 1 to 5 m and a diameter of up to a few 100 m. In the top 2 m here, calcareous peats of different compositions occur besides mud-like deposits with calcareous layers, calcium carbonate grains and mollusc remains (see also Dann 2003). The majority of the described hummocks are situated in the valleys, growing from the valley floors. Some appear on valley slopes and ridges of Pleistocene material in peaty areas, or adjacent to these. Deposition of carbonate sediments is explained by the reduced pressure of ground water, warming of the spring water and the contact with oxygen. Succow, Stegmann & Koska (2001) describe examples of hill-shaped bogs as a result of lateral ground water discharge at Prenzlau and Werder / Beseritz (Neubrandenburg). Paulson (2001) reports small scale bulged bog surfaces in karstic peatlands on Rügen. He interprets these as bog initials resulting from a radial bog water dewatering, rather than as spring fed cupolas. Stegmann (2005) examined bogs situated on slopes in the Sernitz valley (Brandenburg) and identifies strongly calcareous peats, moderate calcareous peats and spring fed peats with low $CaCO_3$ content. Hummocks of 20 m in diameter and 2 m in height are also found at Lake Malchin (Mecklenburg-Vorpommern; W. Schulz, personal comm., March 2010).

Observations are also reported from Schleswig-Holstein. Meyn (1848) mentions tufa at Sielbek (presumably near Ratekau / Lübeck), due to solution of underlying "coral sandstone" (Quaternary sands, rich in calcium carbonate). Schuster (1926) describes the massive spring calcareous sediments at the Keller lake (see also Heck 1946b). Schuster (1926) mentions a spring fed swamp delta as a morphological form at the Keller Lake, which was formed by the ground water exfiltration and corresponding calcareous sedimentation. Unfortunately this delta was removed by limestone quarrying (Thienemann 1922, Peters 1955). According to Schuster (1926), the formation of spring-related calcareous sediments at the Keller lake started during the Atlantic period. This author mentions increased rainfall and spring water formation /source activity associated with higher temperatures as reasons for an enhanced formation of spring-related calcareous sediments at this time. The same author sees the Subboreal to hold favorable conditions for the sedimentation of spring-related calcareous sediments, with drier and warmer conditions compared to today's environments, resulting in more water and less carbon dioxide in the system. Raabe (1980) describes spring-related calcareous hummocks as visible morphological elements from the Curau bog as well as the valleys of Langballigau, Geltinger Au, Delvenau, Steinau and Habernis (fig. 1). These sites are concentrated on the Weichselian moraine landscape with its calcium carbonate-rich sediments, such as tills. With the Prussian Geological Survey calcium carbonate-rich sediments (tufa) were documented at least partially systematically, as with the occurrence in Schleswig Tiergarten and south of Klensby (Heck 1943, fig. 1). The biotope register for Schleswig-Holstein (first version from 1978 to 1994) has systematically mapped a large number of existing spring fed peat hummocks. The main occurrences are in the Weichselian moraine landscape, especially in the valleys. Most of the hills consist of peat, so that calcareous sediments only play a minimal role (Hansen & Martin 2013). Grube & Usinger (2016) report on actual studies of structure and age of peat hummocks at Habernis and Curau bog (fig. 1). All forms from North Germany mentioned are of Holocene age.

So far little information exists about the hydrogeological conditions of spring areas in Schleswig-Holstein (Martin 2004). This situation, as well as the neglect of hydrogeological aspects in the practical implementation of moorland protection programs are also reported from the federal state Mecklenburg-Vorpommern (see Precker 2001, Dann 2003, Kaiser et al. 2012). In summary at least for northern Germany, little recent information is available on the geology-hydrogeology of natural springs and the corresponding tufa.

4. Geological and hydrogeological conditions at the Farbeberge

At the Farbeberge a salt structure in the form of a Keuper-pillow forms the deep geology (Hinsch 1991, Baldschuhn et al. 2001; Reinhold, Krull & Kockel (2008, fig. 1). According to Hinsch (1991) the investigation area is located over a north-south trending buried valley offshoot, ending slightly to the north and being connected to an Elsterian buried valley system cutting >100 m below ground. The area is situated on the western flank of an ice-pushed moraine (see Picard 1962, Stephan 2004), which sweeps from Oldenbüttel over Nindorf towards Tappendorf (fig. 2). Its surface is characterized by a cohesive, chalk rich till of the Middle Saalian (MIS 6; Ehlers et al. 2011). The valley of the Rüterbek down from Nindorf shows a filling of solifluction material, partially covered by peats and subordinate sands. According to Picard (1962) and Stremme (1966) the southern Farbeberg is a fen-area ("Niedermoor"), the northern Farbeberg was mapped as a raised bog-area ("Hochmoor") (fig. 3). Stremme (1966) mentions the occurrence of bog iron ore adjacent to the peat hummocks. The calcium carbonate deposits at the southern Farbeberg were previously mined for amelioration material and for the production of color raw material. Petersen (1892) observed walls of 5 m high calcareous muds in the former pit, covered by 1 m peat ("Moorerde"; see also Wetzel 1927, Heck 1946a). Petersen (1892) described in great detail the deposits, that obviously were precipitated in association with plants. In the sediments he found a remarkable number of gypsum crystals. Blue iron ore (Vivianite) was also encountered in larger quantities. This author sees leaching of the chalky till as source for the calcareous parts of the peat hummocks. Overviews of groundwater levels are prepared by the LLUR (State Agency for Agriculture, Environment and Rural Regions, Flintbek; H. Angermann). Thereafter the groundwater flow within the subsurface aquifer is directed to west-northwest, the interpolated groundwater levels range between +35 and +30 m a.s.l. at the two hummocks.

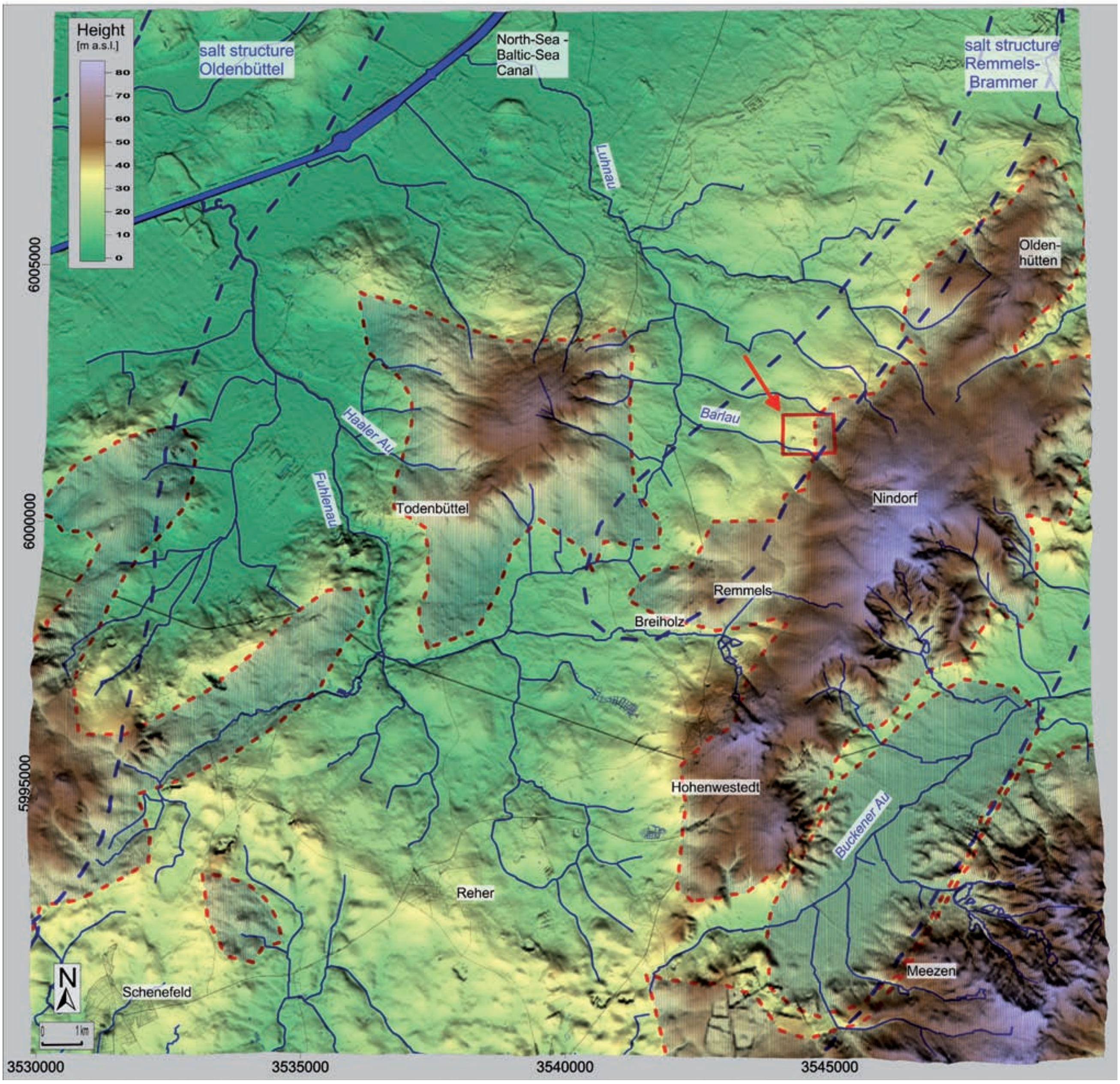

Fig. 2: Large-scaled morphology (DGM). Outline of salt structures according to Reinhold, Krull & Kockel *(2008, blue dotted line). Glacitectonically influenced areas shown in hatched signature and red outline (according to* Stephan *2004). Detailed study area (fig. 3) is shown as a rectangle (data basis topography: LVermGeo-SH).*

Abb. 2: Großräumige Morphologie (DGM). Umrandung der Salzstrukturen nach Reinhold, Krull & Kockel *(2008, blau, diagonale Signatur). Glazitektonisch beeinflusste Bereiche (nach* Stephan *2004, Kreuzsignatur, rote Umrandung). Das engere Untersuchungsgebiet (Abb. 3) ist als Rechteck dargestellt (Datengrundlage Topographie: LVermGeo-SH).*

5. Material und Methods

In addition to the evaluation of archival boring documents (Geological Survey Schleswig-Holstein) several new boreholes were drilled. Hydrogeological information was collected as part of this process. However groundwater monitoring wells are missing in the investigated area, so the groundwater potential distribution and the spatial ascent behavior of groundwater could only be approximated. Nine cores were drilled using the Usinger Drill (Mingram et al. 2007) in order to obtain undisturbed material for palynological investigations and the recovery of materials for ^{14}C- determinations (calcium carbonate, peat, wood) in the years 2011 to 2014. The core drill used was driven by man power, starting at a depth of about 3 metres in very solid sediments on the northern Farbeberg an engine hammer had to be used. This was necessary due to the high ductility of the deposits and the specific mechanical properties (interlocking of the irregularly shaped, tufa deposits). The very high mechanical strength of the underlying deposits partly led to discontinuation of drilling. Cores Fab1-1 and Fab1-2 were supplemented by machine driving core drillings to reach the sediments underlying Eemian organic sediments. The preparation of the pollen samples was carried out at the Institute for Ecosystem Research at the Christian-Albrechts-University of Kiel.

45 soil samples collected in the cores were examined in the Building Materials and Soil Testing Office of the State

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Office of Transport Schleswig-Holstein (Kiel) and the State Laboratory in Neumünster (Division 5, environmental monitoring) for grain size distributions (E DIN ISO 11277: 06.1994, DIN 19683 Part 1 + 2, DIN 18123), loss on ignition (organic constituents; DIN ISO 10694: 08.1996) and calcium carbonate content (DIN 18129).

Spring water sampling for chemical analysis was carried out by the LLUR at 2 locations in Habernis, 1 sample from the Wolsroi spring, 2 samples from Curau bog and 2 from the southern Farbeberg. Suitable spring areas on the northern Farbeberg were not available. Basic parameters were recorded on site and the samples tested by the State Laboratory Neumünster on main parameters.

As basis for digital terrain models and their evaluation DGM1 data of the State Office for Surveying and Geoinformation Schleswig-Holstein (LVermGeo-SH) were available with a height resolution of ca. 0.2 m (laser scanning aerial survey from 2005–2007). Morphological analysis was executed with SURFER (Golden Software Inc., Colorado, USA).

The mineralogical investigations were carried out at the Mineralogical-Petrographic Institute of the University of Hamburg (J. Ludwig) by powder diffractometer from Philips (X`pert System) with the following components: Cu fine focus X-ray tube (glass), Wavelength = 1.540598 A; Graphite monochromator secondarily, automatic divergence aperture increment 0.02 ° 2 theta, beat 1sec / step. Samples were taken of two cores of the following depths: Fab1: 0.86 m, 3.6 to 4.00 m, 4.7–5.2 m, 6.70 m, 7.78 m; Fab2: 2.46 m, 3.06 m, 3.10–3.20 m.

Well preserved gastropods from the Eemian tufa were identified by Professor Klaus Bandel (Buchholz / Nordheide).

The ^{14}C AMS datings were carried out at the Leibniz Institute of Kiel University. The samples were treated by Dr. A. Dreves (written message, 2014) as follows: "The peat and mud probes were inspected and freeze-dried. To obtain the carbonate fraction the dried material was hydrolyzed with a 60% H3PO4 at 90 ° C. The CO_2 of all samples was then reduced with H_2 at 600 ° C over an iron catalyst to graphite and pressed the iron-graphite mixture in a sample holder for the AMS measurement. The ^{14}C concentration of the sample is obtained from the comparison of the determined simultaneously ^{14}C, ^{13}C and ^{12}C contents with those of the CO_2 measurement standards (II oxalic acid) as well as suitable effect zero samples. The conventional ^{14}C age is calculated then by Stuiver & Polách (1977) a correction to isotope fractionation using the same measured with AMS ^{13}C / ^{12}C ratio was applied. The translation into calendar ages was made for the organic samples using the OxCal V4.2 program (Bronk Ramsey, C., Radiocarbon 51 (2009), 337–360) and the IntCal13 calibration sets (Reimer, P., et al., Radiocarbon 55 (2013), 1869–1887) ".

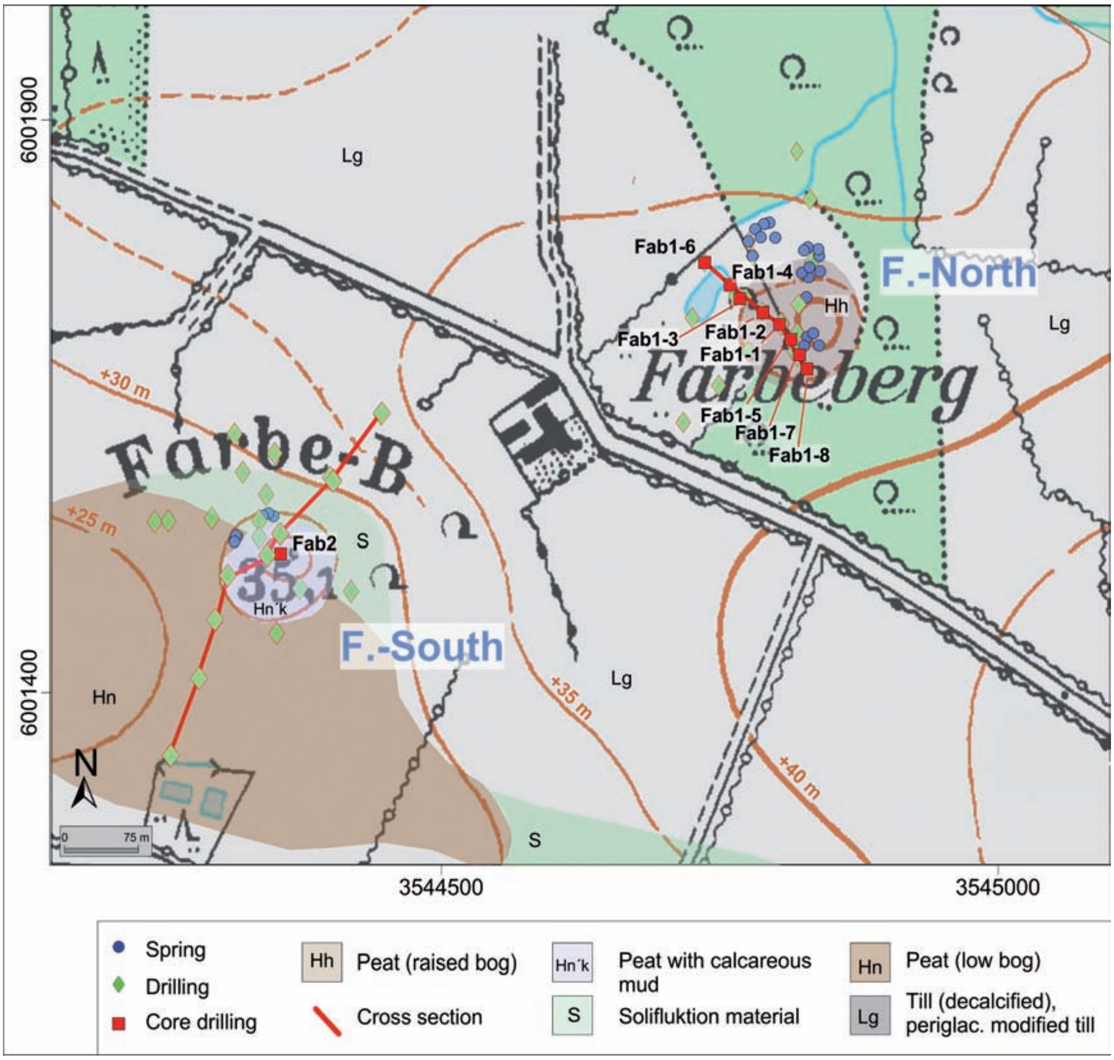

Fig. 3: Map of the investigation area with locally elevated calcareous bogs, position of boreholes, core sampling, geological cross sections and mapped springs (TK25, LVermGeo-SH). Soils according to Picard (1962) and Stremme (1966).

Abb. 3: Lageplan des Untersuchungsgebietes mit Quellkuppen der beiden Farbeberge, Lage der Bohrungen, Kernbohrungen, Profilschnitte und kartierte Quellaustritte (TK25, LVermGeo-SH). Böden nach Picard (1962) und Stremme (1966).

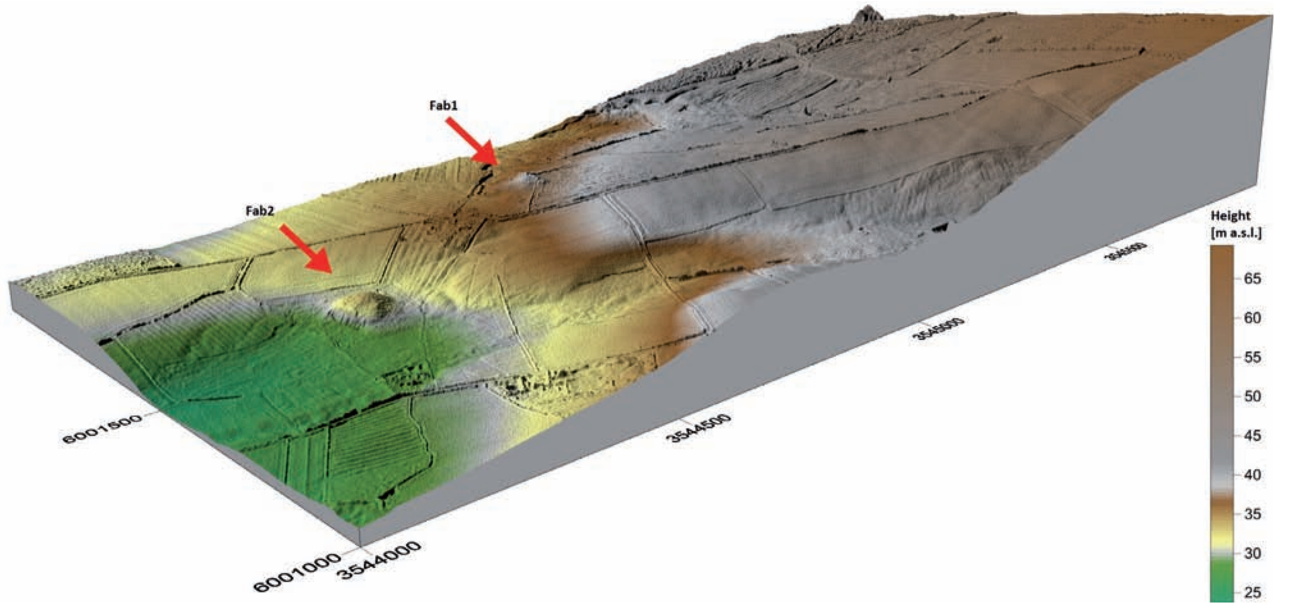

Fig. 4: Digital terrain model (data basis: LVermGeo-SH) with the two prominant peat cupolas Northern and Southern Farbeberg. Distance between coordinate units is 500 m.

Abb. 4: Digitales Geländemodell (Datenbasis: LVermGeo-SH) mit dem südlichen und nördlichem Farbeberg. Die Distanz zwischen Koordinateneinheiten beträgt 500 m.

6. Results

The Farbeberge area comprises two distinct hills of similar size that are located on the northern flank of a wide valley (Rüterbek), most probably formed during the Weichselian. Another round and flat peat hummock is situated east of the northern Farbeberg (see Picard 1962). A lineament is indicated which could pass through the two Farbeberge and another roundish peat area about 300 metres to the east. This linear glacitectonic structure has not yet been adequately explored. The southern Farbeberg has a height of about 3 m (+30.30 to +33.30 m a.s.l.). It is slightly elongated NW-SE perpendicular to the large-scale morphology of the slope (fig. 4). The southern edge of the hummock is characterized by a steep side as a result of the former extraction of carbonate sediments. The original shape of the hummock was changed through the reduction in volume and subsequent slumping (Heck 1946b reports 4.6 m peat). The hill today is mainly used as pasture. The northern Farbeberg has a height of about 2 m; it lies higher (+36.75 to +38.75 m a.s.l.) on the slope than the southern Farbeberg. It is slightly elongate, SE-NW normal to the slope and perpendicular to the large-scale morphology. Two small valleys at the NW' and NE' flanks of the northern Farbeberg (water flows into the Limbrookgraben after 300m) are probably due to strong spring activity during the Holocene. A yet stronger spring activity is assumed under natural conditions. The southern half of the hummock is used as pasture; to the north trees and reed dominate.

6.1 Southern Farbeberg

The geology of southern Farbeberg shows a 3 metres thick sequence of calcareous, clearly layered deposits (fig. 5) on top of glaciofluvial sediments. The younger, Holocene calcium carbonates form mainly calcareous muds with intercalated tufa. Carbonate concentrations are generally more abundant in the lower parts than in the upper. To the top a peat follows, approximately 1 m thick. The geological cross section (fig. 6) shows that the calcareous mud reaches a thickness of more than 1 m. The described conditions are representative for typical tufa/-peat hummocks of North- West Germany. As mentioned above, larger parts of the southern part of the hill were removed (Petersen 1892), thus this part of the hummock information is missing. ^{14}C-ages on the lower tufa range between about 10,750 and 12,520 cal a BP (Tab. 1; lowermost sample is not consistent with upper samples, samples possibly interchanged). Accordingly, the majority of calcium carbonate sedimentation took place during the Preboreal – an interpretation that is supported by the pollen analysis (3.95 m; 3.70 m). Pollen analysis indicates that the Boreal is between 2.95 and 2.35 m, Atlantic between 1.65 and 0.80 m and Subboreal at 0.20 m.

6.2 Northern Farbeberg

6.2.1 Saalian and Eemian deposits

The northern Farbeberg (fig. 7) in contrast, is stratigraphically much older and shows a much more complex structure (fig. 8, 9). The base of the drilled organic sequence is composed of Middle Saalian (MIS 6) till at ca. 11 m depth. The till is relatively soft in the top 2 metre and shows some intercalated sands, which show partial flow structures with a vertical orientation, attributed to artesian groundwater conditions. The sands at the base of the depression show organic constituents in places. These sediments belong to the Saalian lateglacial. The base of the depression is irregular (fig. 9), two steep sided cavities in the profile section can be interpreted as flushing areas of the artesian groundwater. Alternatively a glaci-tectonic influence may be the cause with the sand blocks serving as climbing paths for groundwater.

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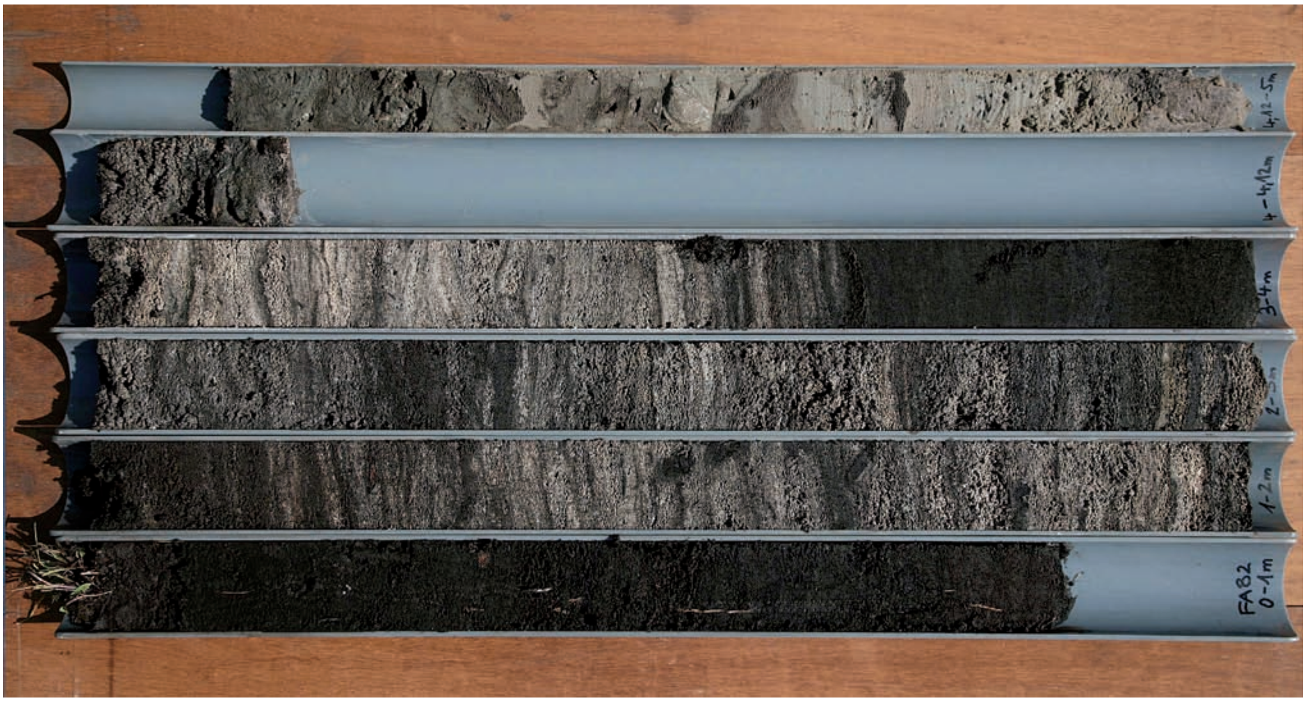

Fig. 5: Photo of drill core from the southern Farbeberg (Fab2). Visible are the peats and intercalating calcareous precipitates (bright colors), the base is built up from sandy deposits of the Pleistocene. Length of a core-liner is 1m.

Abb. 5: Kernphoto des südlichen Farbeberges (Fab2). Erkennbar sind Torfe und Mudden (dunkel) und eingeschaltete Kalkausfällungen (hell), die Basis wird durch sandige pleistozäne Ablagerungen gebildet. Die Länge eines Bohrkernliners beträgt 1m.

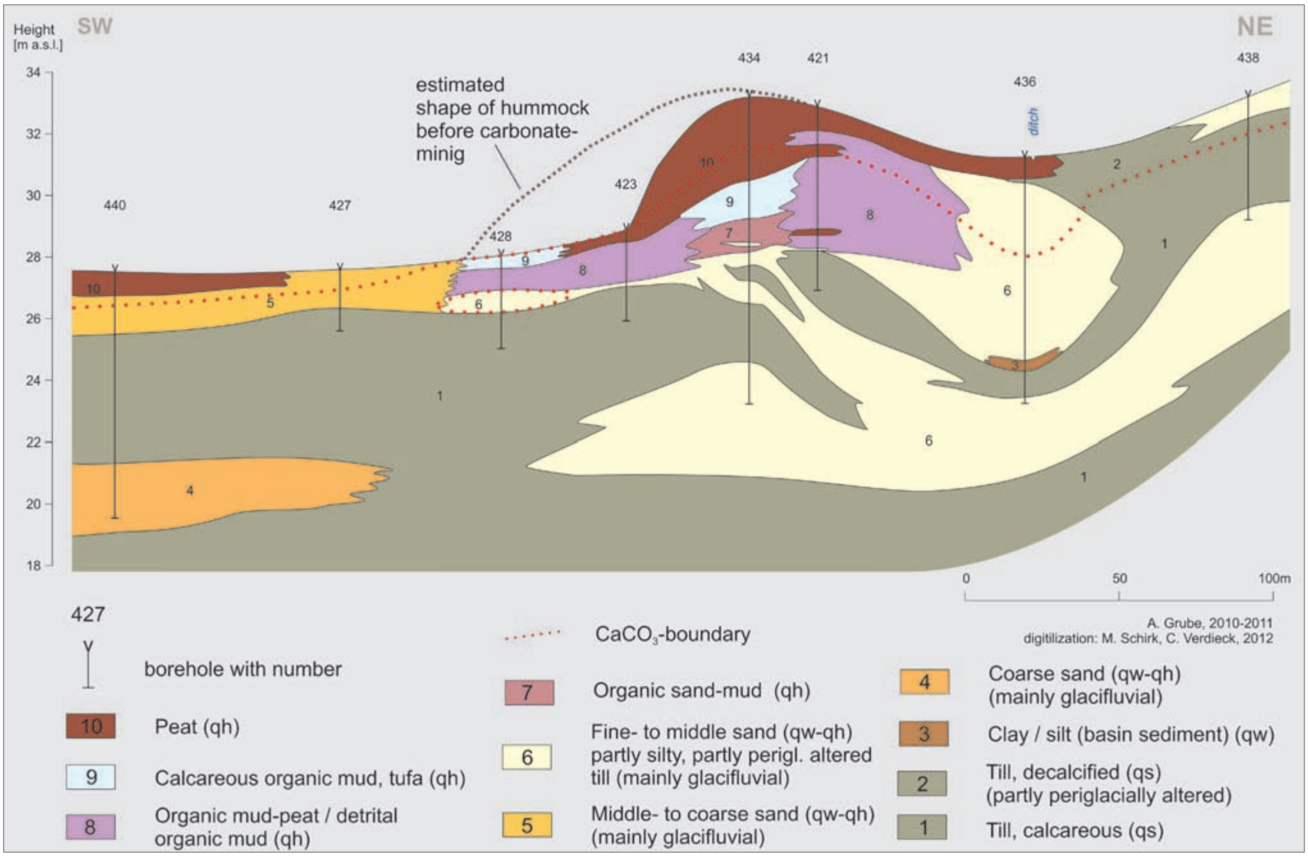

Fig. 6: Simplified geological cross section through the southern Farbeberg (height exaggerated). The shape of the hummock prior to mining of carbonates estimated. Abbreviations: qs=Saalian; qw=Weichselian, qh=Holocene).

Abb. 6: Vereinfachter, stark überhöhter geologischer Profilschnitt durch den südlichen Farbeberg (überhöht). Ungefähre Form der Kuppe vor dem Abbau von Kalken. Abkürzungen: qs=Saale-Komplex; qw=Weichsel-Kaltzeit, qh=Holozän).

Fig. 7: View of the northern Farbeberg. Visible in the foreground the groundwater exfiltration at the foot area of the locally elevated bog. Two persons for scale.

Abb. 7: Blick auf den nördlichen Farbeberg. Im Vordergrund der nasse Fußbereich des Quellhügels mit Grundwasseraustritten. Zwei Personen als Größenmaßstab.

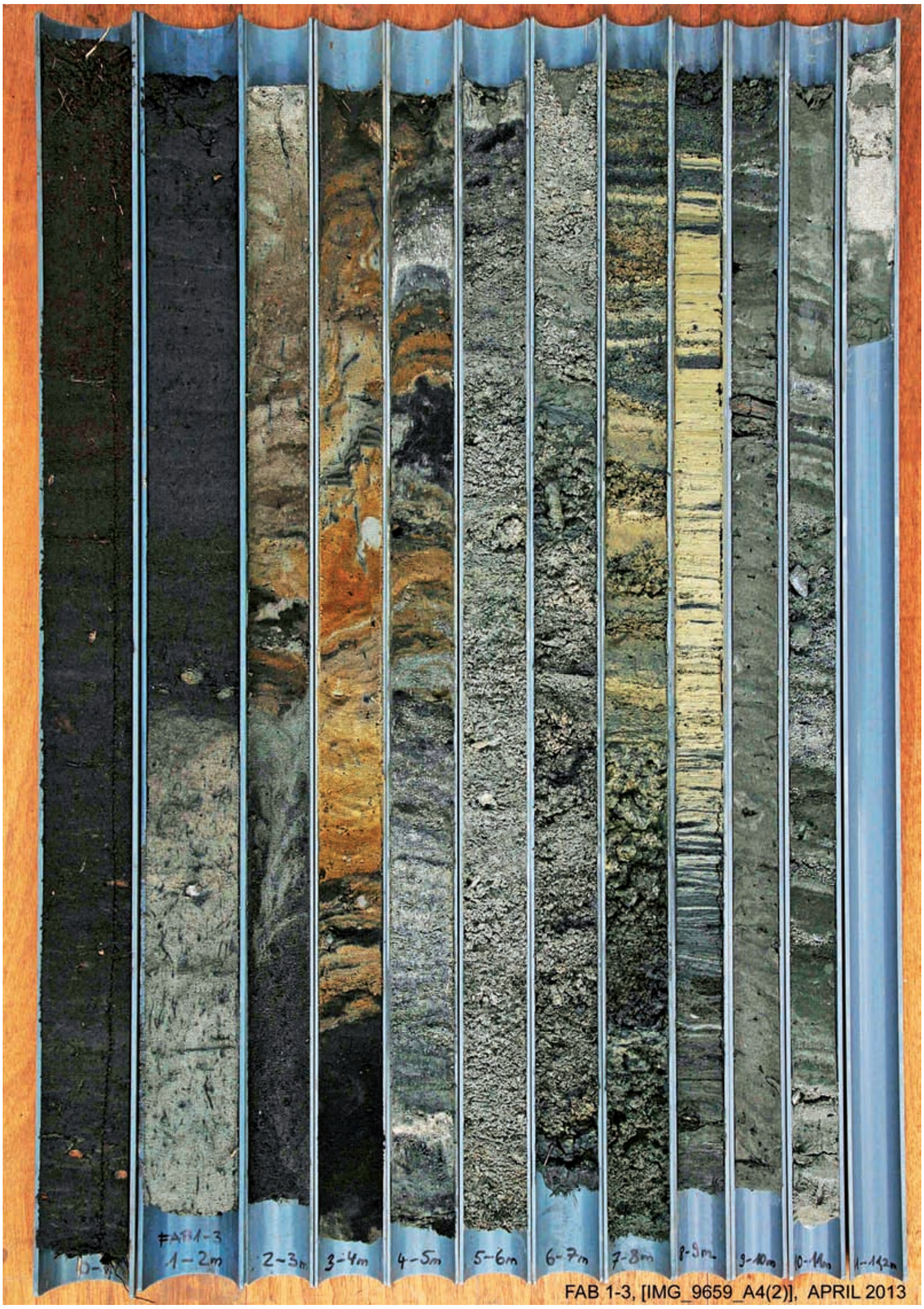

Fig. 8: Photo of drill core from Farbeberg (Fab1-3). Visible are the underlying stadial and interstadial humic sediments of the late-Saalian, succeeded by yellowish fine sediments and coarse tufa of the Eemian, sandy deposits of the Weichselian (partly brownish oxidized) and finally Weichselian Late Glacial to Holocene peats. The diameter of the drill core is 55 mm, the length of a core-liner is 1m.

Abb. 8: Kernphoto des nördlichen Farbeberges (Fab1-3). Erkennbar sind liegenden stadialen und humosen Interstadial-Lagen der Spät-Saale, im Hangenden gelbliche Feinablagerungen und grobe Quellkalke und des Eems, die liegenden Weichsel-Ablagerungen (teilw. braun oxidiert) sowie die spätglazialen bis holozänen Torfe. Der Durchmesser des Kernrohres beträgt 55 mm, die Länge eines Bohrkernliners 1m.

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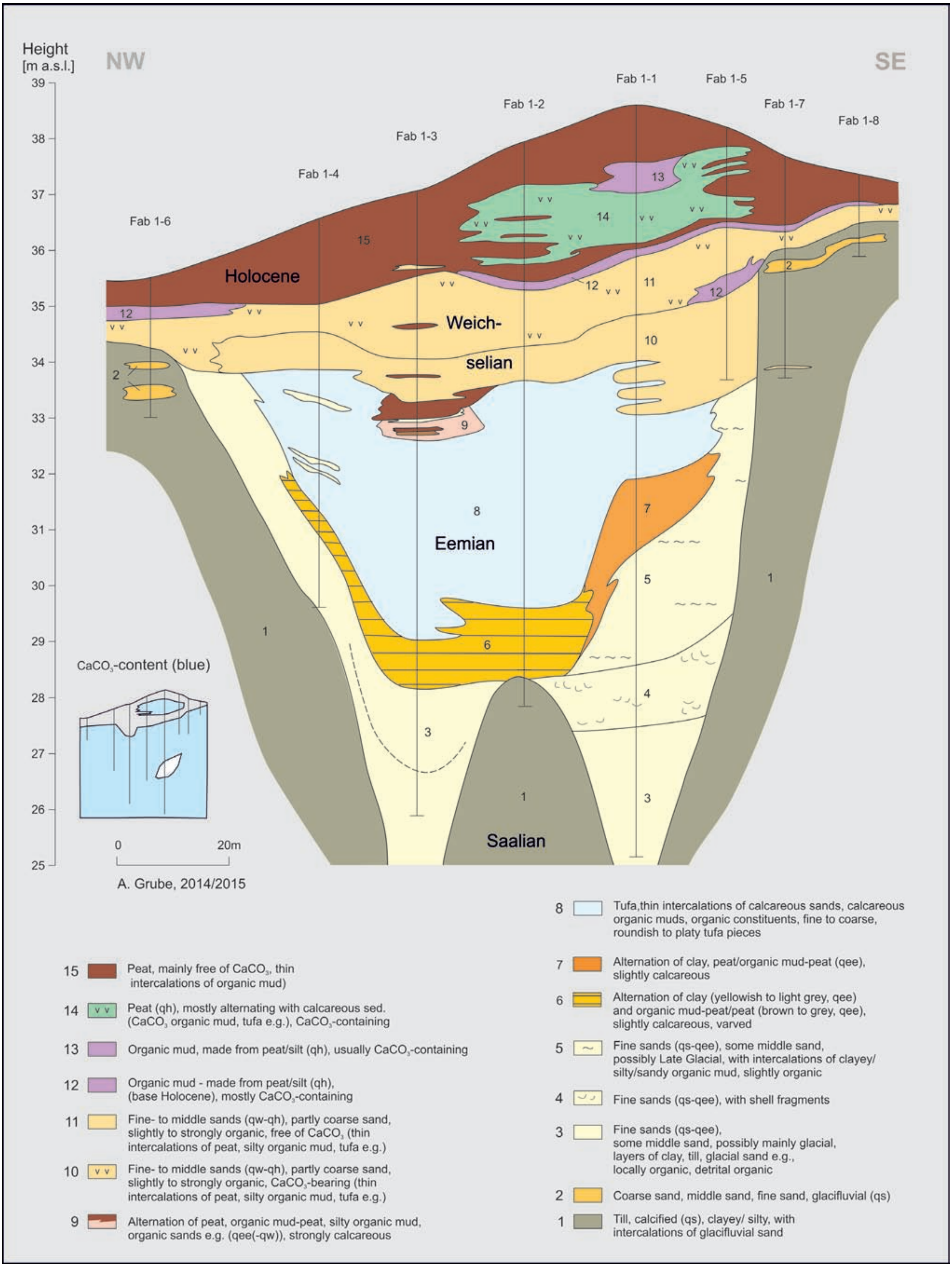

Fig. 9: Geological cross section through the northern Farbeberg (height exaggerated), constructed on the basis of 8 full core drillings. Calcium carbonate dispersal shown in small detail figure.

Abb. 9: Geologischer Profilschnitt durch den nördlichen Farbeberg (überhöht), konstruiert anhand von 8 Kernbohrungen. Kalkverteilung dargestellt in kleiner Nebenabbildung.

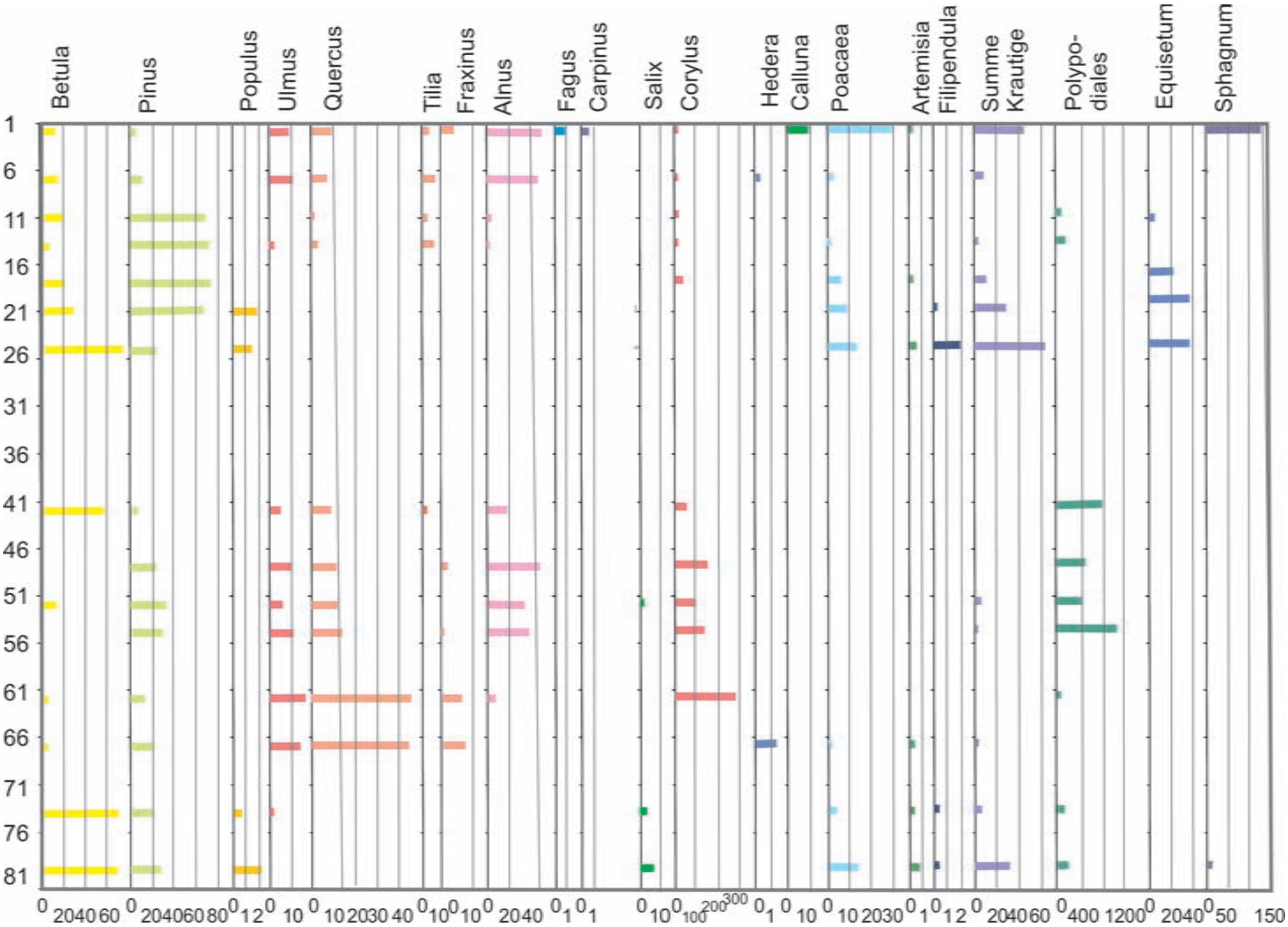

Fig. 10: Pollen diagram Farbeberg-Nord (core Fab1-1). Pollen versus depths.

Abb. 10: Pollendiagramm Farbeberg-Nord (Kern Fab1-1). Teufe gegen Pollenzahl aufgetragen.

Above the glacigenic deposits there is up to ca. 5 m of fine to medium sands and intercalated tufa. In some parts of the hollow massive tufa with a thickness of several metre occurs. In another area the sediments are rhythmically bedded. The pollen diagram for core Fab1-1 (fig. 3) is shown in fig. 10. The Eemian sequence shows pollen zones E-I, E-I-II, E-III and E-IVa, b and E-VII. E-IVb shows a large quantity of reworked material. Zones E-V and E-VI are missing. A higher-resolution pollen analysis is in progress.

The tufa forms the bulk of the sintered calcium carbonate deposits of the section (fig. 8). These are represented by solid white to grey (locally ocher), cellular-porous limestone, often sharp edged, partly roundish, partly with a columnar shape. In many cases, prints of plants can be recognized in the tufa. Larger pieces of several cm in length often show massive, bulbous tufa, which are associated with platy to circular elements that were enclosed by calcium carbonate. Tube-shaped tufa is found in core Fab1-2 between 6.5–7.5 m. The columnar forms are thought to have been formed by calcium carbonate precipitation around reed-caulis. The precipitated material is predominantly calcite, gypsum and pyrite. Aragonite occurs only locally (analysis by R. Ludwig, Univ. of Hamburg). Some well preserved snails and mussels have been found. The gastropods *Bithynia tentaculata*, *Planorbis planorbis* , *Gyraulus cf. laevis* and *Radix peregra / baltica* were identified by Prof. Klaus Bandel (Buchholz i. d. N.).

Partly layered sediments occur, that have a honeycomb-like appearance. The sequence is characterized by an alternation of clayey-silty and fine sand layers. According to the macroscopic investigation this is a sedimentary deposit without major plant and larger animal remnants. The entire sequence is strongly calcareous, and could show an annually layered sediment (e. g. Andrews & Brasier 2005). Several hundred layers are differentiated with sub-millimeter thickness. The thickness of the layers is variable; in the clayey and silty parts they are difficult to differentiate, even under a binocular microscope. While showing yellow colors in a fresh state, the sediments appear as being brown after drying. Sometimes reddish-brown areas are present apparently having a high iron content.

The overall carbonate content in the cores of the northern Farbeberg (Fab1-2, Fab1-3, Fab1-4, Fab1-5) reaches up to 100% (45 samples). The $CaCO_3$ contents in the Eemian deposits are significantly higher than in the Holocene. Total carbon (total C) contents amount to 12–45 cg/g and 9 and 34% by mass. The Eemian sediments have a lower areal extent than the peat formed during the Lateglacial and Holocene, most likely owing to erosion during the Weichselian. Spring areas (fig. 3) are mainly found to the northern side of the northern Farbeberg. They have been destroyed or hidden because of the agricultural as pastures on the southern side.

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6.2.2 Weichselian deposits

Medium to fine sand overlies the Eemian carbonates. It is up to 3 m thick and contains gravel with smaller erratics. This layer is assumed to belong to the Weichselian. The horizon is complex in structure and partially organic (fig. 8, 9). In the eastern part, the upper areas show a higher organic content, but overall the proportion of humic content is higher in the bottom half of the total sequence. In the upper sequence (core Fab1-3), there are also thin peat layers. On the basis of the calcium carbonate content a subdivision into a lower and an upper section is possible: The lower part of the sand is calcareous, the upper part is decalcified. The general boundary of calcium carbonate parallels the base of the raised peat hummock and the top of the till. Since the Saalian tills at the east are higher, the boundary of calcium carbonate is higher here also. Local depressions of the boundary can be observed, possibly being a result of a local concentration of organic deposits and a greater influence of humic acids. Locally flow textures can be noticed, that include cone-shaped sink marks, structures resembling cryoturbations and solifluction movements as well as en-echolon offsets. Organic constituents are found floating around erratics (core Fab1-4), possibly being dislocated periglacially. Other dislocations may be a result of flow movements and mass wasting in an environment with a strong vertical ground water activity. Eye catching in this sequence is the brown colouring caused by oxidation, the result of seepage by oxygen-containing groundwater. Sandy intercalations are present, locally possibly due to frost lenses or fluvial input. Calcium carbonates have been dated by ^{14}C method (tab. 1) giving ages from core Fab1-3 of 44,785 + 1819 / -1482 ^{14}C cal a BP (2.46 m below ground), and 8,354 at + 58 / -57 ^{14}C cal a BP (2.85 m below ground). A sample from a depth of 2.12 m below ground gave an age of >51,050 ^{14}C cal a BP years.

6.2.3 Weichselian Lateglacial and Holocene deposits

A limnic-telmatic sequence forms a peat hummock above the Weichselian sediments. This Lateglacial to Holocene sequence is characterized mainly by peat of up to 3 m thickness. The peats are strongly calcareous to decalcified (fig. 8). In the central areas of the northern Farbeberg hummock thicker calcareous deposits are intercalated in the peat. The Holocene calcareous deposits are thinner than those at the southern Farbeberg. Locally wood can be found at the base of peat accumulations. ^{14}C age determinations on the calcium carbonate deposits, taken from depths of 0.86, 1.27 and 2.42 m below surface in core Fab1-1 at the highest point of the hummock (fig. 8; tab. 1) show ages between 12,430 and 11,280 ^{14}C cal a BP. Although these ages are vertically inconsistent, the values are in the transition between Weichselian Lateglacial to Preboreal. Core Fab1-3 is located a few metre further to the west at a more marginal position and shows an age of 11,385 ^{14}C years BP (Preboreal) at 1.51 m below surface and of 8,870 cal a ^{14}C BP (Boreal) at 0.98 m below surface. Even further to the margins of the hummock core Fab1-4 shows an age of 10,004 ^{14}C cal a BP (Boreal) at 1.55 m below surface. Pollen analyses of the upper organic part of core Fab1-1 on top of the dominantly Weichselian material hints to the Meiendorf-Interstadial (2.75 m), covered by Preboreal sediments (fig. 10). The sediments above belong to the Preboreal (2.50 m), transition to the Boreal (2.10 m), Boreal (1.80 m), Atlantic (1.40 m, 1.10 m, 0.70 m) and Subboreal (0.70 m, 0.20 m).

The water table is usually located only a few decimeters below surface. The groundwater is under artesian pressure, presumably being built up under the cohesive till. The recharge areas are expected to be in the hilly, ice pushed areas north and east of the Farbeberge. This idea is supported by the formation of hummocks on the north-

Tab. 1: ^{14}C-values from the Northern Farbeberg (Fab1) and Southern Farbeberg (Fab2).

Tab. 1: Ermittelte ^{14}C-Werte an den Standorten Farbeberg-Nord (Fab1) und Farbeberg-Süd (Fab2).

Core-nr.	Lab.-number	Depths [m b. surface]	cal ^{14}C-age BP [a]	Stand. Deviation [a]	Material	Samples
Fab1-1	KIA48730	0,86 m	11.280	+/- 55	tufa	1
Fab1-1	KIA48731	1,27 m	12.430	+/- 60	tufa	1
Fab1-1	KIA50016	2,41 - 2,42	11.670	+/- 50	tufa	1
Fab1-3	KIA50347	0,98 m	8.870	+/- 35	peat	1
Fab1-3	KIA50348	1,51 - 1,52	11.385	+/- 45	peat	1
Fab1-3	KIA50857	2.46 m	44.785	+ 1819 / -1482	peat / organic mud, leaching residue	1
Fab1-3	KIA50856	2,85 m	8.354	+ 58 / -57	plants from sediment, leaching residue	1
Fab1-4	KIA50349	1,55 m	10.004	+/- 39	wood	4
Fab1-4	KIA50858	2.12 m	> 51.050	-	carbonate*	1
Fab2	KIA 48732	1,77 m	10.995	+/- 55	carbonate *	1
Fab2	KIA 48733	2,46 m	12.110	+/- 60	carbonate *	1
Fab2	KIA 48734	2,78 m	12.520	+/- 60	carbonate *	1
Fab2	KIA 48735	3,38 m	12.230	+/- 60	carbonate *	1
Fab2	KIA 48736	4,08 m	10.750	+/- 45	carbonate *	1

* interpreted as tufa

ern flank of the valley and the very well drained and completely water-filled aquifer in the valley itself with a free ground water surface. Only slightly artesian groundwater conditions were encountered in the boreholes that did not penetrate the confining till. Strong, areal groundwater outflow was observed at the southern artificial flank of the southern Farbeberg at the former mining area. The spring outflows show an anthropogenic influence being located in the area of drainage ditches on the northern Farbeberg. The preferred groundwater outflow at the N / NW slope of the northern Farbeberg is in accordance with the proposed groundwater surface. The same applies to the sources at the northeastern edge of the southern Farbeberg.

7. Discussion

7.1 Geological structure

Raised peat hummocks such as at Nindorf (Farbeberge), Habernis and Curau occur in both Weichselian and Saalian moraine areas and are characterized by the occurrence of peat, organic mud, calcareous mud and tufa. They have diameters of up to 160 m and are up to >3 m high (hummock at Habernis) and lengths of >500 m (peat wall at Curau bog; Grube & Usinger 2016). The hummocks show similar dimensions as those mentioned by Tüxen (1985a, b) from Lower Saxony and Bremer (1996) from Mecklenburg-Vorpommern. The cupolas of the Farbeberge are independent of areal pure carbonate sediments in the deeper subsoil. The hydrogeological conditions show no adjacent contact springs or overflow springs (cf. Von Wichdorff 1904, Von Wichdorff & Range 1906, Von Wichdorff 1914). The groundwater outflows from the Farbeberge are obviously linked to structurally controlled pathways, probably formed glacitectonically with ground water ascending from deeper aquifers.

When comparing the occurrence of spring water hummocks with the distribution of areas influenced by glacitectonism in Schleswig-Holstein, a clear relationship is indicated (fig. 1). Ice pushed areas are often characterized by hydraulic contacts to deeper, artesian aquifers. The dislocation of sediments allow for the built up of stronger artesian pressures and frequent spring outflows. Comparable geological settings with respect to the spring areas are also found in different morphologically high-altitude areas of Schleswig-Holstein, such as the Stollberg and surroundings (Bredstedt, Nordfriesland), where among others, glacitectonically disturbed Miocene mica clays and Holsteinian clays are found, and at the Westensee lake (Rendsburg-Eckernförde). In the Riesewohld area (to the west of Albersdorf, Dithmarschen) on a moraine area (+55 to +60 m a.s.l.) string-like bogs occur, possibly retracing glaci-tectonic structures. In the intensively glaci-tectonically affected area Wacken (Steinburg) numerous springs occur in morphological high positions, which may have partly already existed during the Eemian (Stephan 1981). Spring water outflows in top position on the > +75 m a.s.l. moraine areas northeast of Groß Vollstedt (pers. comm. W. Mevs, LLUR) are likely to be due to glacitectonic deformations.

The chemical composition of the spring waters is very similar at the sites studied (Farbeberge, Habernis and Curau). It is a calcium bicarbonate water with low total mineralization (300 mg/l at the Farbeberge). The temperatures were 10° C, the pH at 7.00 (Farbeberge) to 7.5, the conductivities at 35–50 µS/cm. There is no indication for geogenic salinization of the deep groundwater (e. g. Grube et al. 2000), the NaCl-concentrations are in the order of about 30 mg/l. Influences from agricultural use (nitrate and ammonium) are comparibly low or even missing. Since the studied areas all are regionally situated in agricultural land, it can be assumed that the ascending groundwater comes from moderate or greater depth, the proportion of shallow groundwater is likely to be rather small.

Most Eemian deposits in Schleswig-Holstein are formed in limnic to telmatic environments. Furthermore local diatomite deposits occur, as in central Schleswig-Holstein (Menke & Ross 1967, see also Menke in Stremme & Menke 1980) and western Holstein (Menke & Tynni 1984). Similar deposits have been described from Denmark (Andersen 1965). Eemian tufa has been reported from the Swabian Alb (Dehm 1951). Well known are the Middle Pleistocene tufa from central Germany (Steiner 1981, Kahlke 1984, Mania & Altermann 2004). However, the Eemian tufa and the calcareous honeycomb-like, varved sediments from the northern Farbeberg have not previously been described in Northern Germany. They allow for valuable climatic statements. It has to be further investigated whether annual laminations are present at the varve-like sediments (see Frenzel & Bludau 1987).

The presence of tufa deposits is very diverse at the sites studied. Massive, several metre thick, pure tufa occur at the northern Farbeberg in the lower parts (Eemian). In the Holocene deposits on the northern Farbeberg, in Habernis and the Curau bog calcareous sediments occur as irregular horizons in organic muds and peats, preferably in the lower parts of these sediments. This matches results from other locations, where calcium carbonate precipitates are generally sparsely found in peats, massive calcareous sediment or tufa are but rarely found (Moore & Bellamy 1974). In general, continuation of calcium carbonate sedimentation obviously is very diverse, being rather continuous in Eemian deposits and rather discontinuous in Holocene strata.

At the northern Farbeberg the most massive Holocene carbonate sedimentation are found in the center of the spring fed raised peat hummock, whereas carbonate concentrations are diminishing towards the flanks of the hummock. This can be attributed to stronger dissolution at the flanks due to the stronger percolation of water. The mode of formation of the Holocene carbonates remains uncertain. Though here a subareal genesis is favored, a sub-surface growth of tufa and calcareous muds is – at least in part – generally also possible. An argument for the latter are the peat layers of 1–2 metre thickness that cover the carbonate sediments at the sites Farbeberge, Habernis and Curau. The deposited carbonate could, according to Sendtner (1854), have been formed by humic acids and subsequent re-precipitation by the resolution of snail housings and mussel shells. The massive Eemian tufa shows a precipitation of calcium carbonate around vegetation bodies. This should preferably have occurred subaerial or at least close to the surface or in shallow water. This is also confirmed by the accompanying fauna. The gastropods species composition with *Bithynia tentaculata*, *Planorbis planorbis*, *Gyraulus cf. laevis* and *Radix peregra / baltica* (ident. by Klaus Bandel) argues for small, open water areas with shallow waters during sedimentation. A further differentiation of the several metres thick sediments, mainly consisting of carbonate, with respect to the palaeo-life conditions of the gastropods was thus not possible. The eye catching change of sedimentation style during the Eemian, from yellow-gray, finely layered deposits to almost pure tufa indicates a temporarily altered characteristic of the spring waters. The distinct facies change in sedimentation between clay and tufa could possibly be explained by climatic changes during the Eemian (Dansgaard et al., 1993, Björck et al. 2000, Turner 2000, Müller & Kukla 2004, Müller et al. 2005, Sirocko et al. 2005, Müller 2009).

Presumably, at the northern Farbeberg only a small hummock similar to the present one could have existed during the Eemian, but has since been removed by subsequent erosional processes. Arguments for this are, that zone E-IVb shows a large quantity of reworked material and zones E-V and E-VI are missing; additionally the sequence does not emerge above the surrounding ground. Filling of a small depression – created by erosion of the soft Eemian sediments and / or sagging – during the Weichselian ("6" in fig. 9) by solifluction and periglacial slopewash took place, as well as a possible deposition of calcium carbonate during mid-Weichselian Interstadials. Starting already from the Meiendorf Interstadial (14.500–13.850 a BP) with a probable enhanced spring activity following the reduced occurrence of permafrost led to the deposition of peat and calcium carbonate. The general spatial extension of the Eemian and the Holocene deposits as a result of artesian ground waters at the northern Farbeberg has been constant since the Eemian.

The locations Habernis (Weichselian landscape; Grube & Usinger 2016) and Farbeberge (Saalian landscape, this study) are comparable from a geological point of view with respect to the composition of subsurface geology, since cohesive sediments are dominant at both sites: thick, chalk-rich till (Weichselian and Middle Saalian) has widespread occurrence in the shallow. The decalcification of the glacigenic deposits ($CaCO_3$-content up to >20%) during a warm period such as the Holocene, is low – due to the impermeability of these sediments. However, the till of the middle Saalian at the Farbeberge has – despite its age – hardly been decalcified (decalcification depths only a few decimeter) during the Eemian, though this period was more predestined to leaching of calcium carbonate than the Holocene (Menke 1981; Frenzel, Pecsi & Velichko 1992, Müller 2009).

7.2 Age relationships and climatic aspects

The question why tufa deposition are found in the Eemian sections and in the lower parts of the Holocene sediments, can be answered as follows. The catchment area of the outflowing artesian groundwater at the investigation sites must be large scaled, because a pressure gradient of several decimeters above ground level cannot be set up locally. Anyhow this does not mean that only deeper geological strata are acting as the provenance for the calcium carbonate precipitations. Rather, the artesian setting can be built up in deep aquifer sections, letting surface groundwater be incorporated into the emerging spring water. This can be explained by the hydraulic pressure conditions in aquifers, in which the flow velocities grow upwards. Calcium carbonate is released from the still calcareous layers at greater depths which allows for a sedimentation in the form of tufa during a complete interglacial. A decrease in the Holocene carbonate deposition could be explained with the decreasing decalcification (leaching) in the shallow underground during an interglacial. The decalcification along fissures, where the majority of groundwater flow in the till takes place could also have an influence. The Holocene calcium carbonate precipitation at the Farbeberge shows that the decalcification of the landscape in the Lateglacial may still have had an impact. Especially the disintegration of permafrost must have had an influence, it again allowed an extensive flow through the subsurface pore aquifers. Since the underlying sediments still contain much calcium carbonate and an access of the spring water is expected from a greater depth, also changing temperature conditions, and the following variable hydrogeological conditions as well as impacts of vegetation are likely to have influenced the tufa formation. This is consistent with published literature (Gilvear et al. 1993). In summary it can be said that the sedimentation at the Farbeberge reflects a combination of aging and decalcification of the near-surface sediments occurring during the Lateglacial / Early Holocene – which led to preferred calcification during the climatic optimum phases until the end of the Atlantic period.

The spring discharges are likely to be active since the end of the Middle-Pleistocene. However, the Saalian-Lateglacial deposits on the northern Farbeberg are of telmatic origin, they do not contain calcium carbonate sediments. Anyhow in principle, dissolution of existing sediments from this period is possible.

The calibrated radiocarbon ages of the Lateglacial to Holocene deposits show a heterogeneous signal. The oldest tufa are found on the southern Farbeberg (12,520 ^{14}C years BP), the corresponding deposits on the northern Farbeberg show an age of 11,385 ^{14}C years BP. The Lateglacial activity of the springs is in accordance with sites in Poland (Mazurek et al. 2014). It is noteworthy that the dates from the southern Farbeberg indicate predominantly Weichselian - Lateglacial carbonate sedimentation. The ^{14}C-ages on the northern Farbeberg show a much more complex picture. Parts of carbonate and humic sediments in the center of the hummock give Lateglacial ages at shallow depth. This implies that since then, hardly any sedimentation has occurred – or even removal of material (e.g. volume loss by oxidation). At the margins, at least locally, younger sediments are present. This would represent a sedimentation period of only about 3,500 years. Much of the recent carbonate sediments of the Weichselian Lateglacial and Holocene are thus older than the average sediments mentioned by Laumets, Kalm & Zohar (2010) drawn from different works, thereafter the main phase of tufa formation is summarized with 9.4 to 7.4 ka BP. Accordingly the "late Holocene tufa decline" is irrelevant at the investigated sites.

The dating of carbonates is problematic, due to the hard water effect, possibly even a reservoir effect (Srdoc et al.

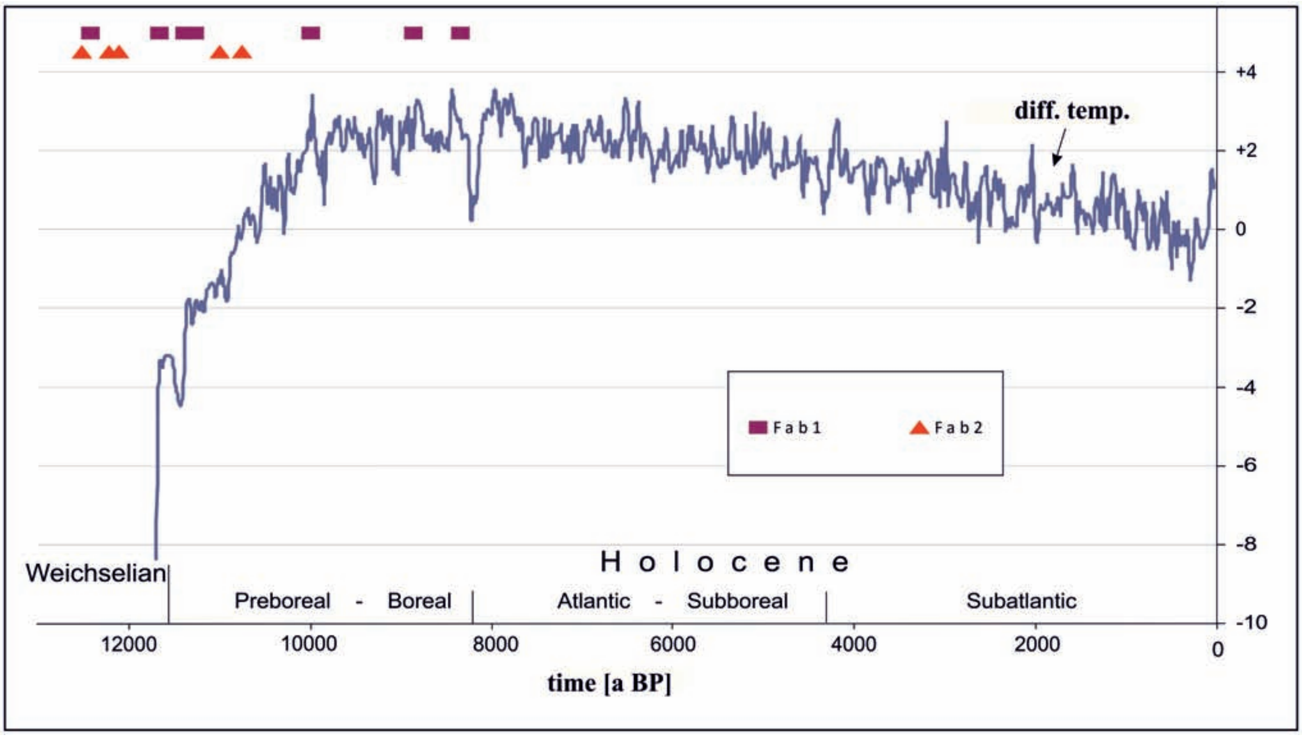

Fig. 11: Climate curve of the Holocene showing the ¹⁴C-ages from this study (tufa, peat, wood) in front of climatic curve since the Weichselian Late Glacial (deviation T [°C]; data: ice core Greenland, Vinther et al. 2009). Absolute ages for Holocene taken from draft Subcommission Quaternary 2015.

Abb. 11: Klimakurve des Holozäns mit Darstellung der ¹⁴C-Alter dieser Studie (Kalke, Torf, Holz) vor dem Hintergrund einer Klimakurve seit dem Spätglazial (Abweichung T [°C]; Daten: Eiskern Grönland, Vinther et al. 2009). Absolute Altersangaben Holozän nach Entwurf Subkommission Quartär 2015.

1980, 1983; Wagner 1995; Lowe & Walker 2015). Uncertainties also occur through the use of different dating material (calcareous mud / tufa, peat). Mostly, there are problems in the allocation of the carbonate / tufa deposits in terms of their genesis. Carbonates with a small thickness it cannot be decided without detailed investigation, whether these chronostratigraphically belong to the corresponding unit or are influenced by older calcareous waters moving into a younger peat body. The high ^{14}C-ages even at low depth at the Farbeberge suggest such processes (core Fab1-3 shows an age of 11,385 ^{14}C cal a BP / Preboreal at only 1.51 m below ground). This effect would be expected in principle, on the northern Farbeberg, due to the massive carbonates in the Eemian deposits, which are traversed by the artesian groundwater. However, this aspect can possibly be neglected, because the carbonates on the neighboring southern Farbeberg also show high ages, while massive carbonates of the Eemian here are missing. At the southern Farbeberg the limnic to telmatic sedimentation and tufa sedimentation started already during the Weichselian Lateglacial. At the northern Farbeberg similar ages with 12,520 ^{14}C cal a BP are present. Although the determined ages do not show a continuous age series, the values are similar and provide a plausible picture.

Thickness, type and composition of the Eemian deposits prove a much stronger carbonate sedimentation during the Eemian than during the Holocene. As a result of the higher mean annual temperatures (cf. Menke in Stremme & Menke 1980, Menke 1981, Kühl et al. 2007) higher groundwater temperatures are to be expected, which in turn led to a reduced solubility of $CaCO_3$ in the subsurface. Menke (in Stremme & Menke 1980) sees the quantitative preservation of diatoms, or diatomaceous earth in the Eemian to be an effect of greater supply of silica due to intense weathering and greater seepage (higher precipitation, or leachate). The same is assumed for the solution of $CaCO_3$ from the surface sediments. After the dissemination of climate indicators such as Ilex and Hedera the climate optimum correlates to the Younger Eemian (Menke, in Stremme & Menke 1980 Rundgren, Björck & Hammarlund 2005). This is in accordance with the detected pollen zones (Zones V and VI are missing) at the Farbeberge.

Currently it is unclear whether the ^{14}C-dated carbonates in the intermediate layer between the Eemian and the Holocene sediments are due to an interstadial sedimentation, or go back to solution and re-precipitation of Eemian tufa. The striking age-differences can possibly be explained by contamination of the samples. Anyhow within the closely spaced dates at the northern Farbeberg a carbonate precipitation during Weichselian interstadials seems possible. This is consistent with interpretations of Jäger & Lozek (1968), that mention interstadial carbonates (“impure travertine”) above travertinized Eemian tufa. The drilled carbonates could allow for future investigation of Weichselian carbonate deposition at the Farbeberge site, because carbonate precipitation is not likely in permafrost conditions (Makhnach et al. 2004).

8. Literature

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