Reconstruction of the fire history in the *Siedlungskammer* Burgweinting (Bavaria, Germany) in relation to settlement and environmental history

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Abstract: Palaeoenvironmental investigations were carried out in the *Siedlungskammer* (prehistoric settlement area) Burgweinting (Regensburg, Bavaria, Germany) to reveal past settlement conditions and human impact on the environment. Two sequences were obtained from the Islinger Mühlbach Fen, in close proximity to the archaeological excavation site in Burgweinting, which documents an almost continuous settlement history since the Neolithic Period. The analyses of the sequences comprise stratigraphic, geochemical and microscopic charcoal analyses. For chronological information, radiocarbon dating was conducted on a total of 10 samples. Thus, the first long-term fire record was reconstructed for the investigation area, and the results were correlated, based on radiocarbon dating, with the available environmental information and settlement history in the *Siedlungskammer* Burgweinting. The fire record reveals an almost continuous, but alternating fire history. Furthermore, it shows that fire played an important role in the *Siedlungskammer* Burgweinting and that most probably as early as the Mesolithic hunterer–gatherers deliberately used fire.

Fire is, beyond a doubt, an important abiotic factor affecting the environment. Biomass burning affects, in particular, the vegetation cover and woodland composition. During prehistoric times, fire was used for land management, wildlife management, and domestic use (Bowman *et al.* 2009). The anthropogenic use of fire is, in turn, associated with activities such as agriculture, firewood gathering, etc., which affect ecosystems in a diverse manner. To reveal the fire history of a prehistoric settlement area is therefore a vital part of palaeoecosystem research with regard to human–landscape interaction.

The occurrence of fire is directly evidenced by particulate charcoal incorporated in soils, sediments and peat (e.g. Whitlock & Larsen 2001; Conedera *et al.* 2009). Because of the resistance of charcoal to microbial attack, the particles persist over thousands of years and can be used for the reconstruction of fire history (e.g. Tolonen 1986). Numerous studies using charcoal analyses have been carried out that are related to the issue of fire–climate–vegetation relationships (e.g. Beaty & Taylor 2009), human impact on the environment and an archaeological context (e.g. Marguerie & Hunot 2007; Marinova & Thiebault 2008). As a consequence, many different methodological approaches, especially concerning laboratory and counting procedures as well as data processing, have been applied, and there has been controversy related to these in the literature (e.g. Rhodes 1998; Carcaillet *et al.* 2001; Whitlock & Larsen 2001; Conedera *et al.* 2009). Concerning the interpretation of the records, many questions still remain unanswered. The charcoal records possibly comprise both charcoal derived from natural lightning-induced fires and charcoal produced by anthropogenically ignited fires (e.g. Edwards & Whittington 2000). The incidence of natural fires depends on the availability of combustible material (presence of wood, wood species, grass) and on climatic conditions. Based on the assumption that wildfires in Central Europe are rare because it is thought that the woodland composition is not flammable (Ellenberg 1996), the charcoal records are interpreted to reflect the deliberate use of fire by humans.

The study area, *Siedlungskammer* (prehistoric settlement area; clearing for settlement surrounded by woodland) Burgweinting (central Bavaria,

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Germany), offers an ideal setting to study past environmental conditions and the human impact on the landscape, as a result of the assemblage of archaeological evidence in combination with the presence of geoarchives. The *Siedlungskammer* Burgweinting is part of the Regensburger Altsiedelland, one of the oldest settlement areas in Central Europe, where settlement history can be traced back to the Palaeolithic period (Torbrügge 1984; Schier 1985; Paetzold 1992) (Fig. 1). The physiogeographical conditions of a moderate climate and very productive soils, combined with a close proximity to the river Danube traffic route, have attracted human populations ever since. An archaeological excavation in the *Siedlungskammer* Burgweinting has been continuing since 1994, and has delivered excellent insight into the spatio-temporal distribution of prehistoric cultures from the Linear Pottery Culture (Neolithic Period) to the Middle Ages (Stadt Regensburg *et al.* 2004). An area of *c.* 40 ha has been excavated, and the site has become one of the outstanding excavation areas in Central Europe.

In this paper we present the first long-term fire history record for the Regensburg region. We investigate the question of whether the different settlement periods evidenced by the archaeological excavations are reflected in the geoarchives. Therefore, multi-proxy investigations comprising stratigraphic, geochemical and microscopic charcoal analyses as well as radiocarbon dating were carried out on the Islinger Mühlbach Fen, in close proximity to the excavation site. In this paper, we present the results of two profiles: a long peat profile (profile 7038-302) from the centre of the fen, and a peat–colluvia sequence from the margin (profile 7038-306). The final aim of this study is to combine the palaeoenvironmental data with the outcome of the archaeological excavations.

Location and physiogeographical setting

The study area *Siedlungskammer* Burgweinting (central Bavaria, Germany) is located south of the river Danube on the southeastern outskirts of Regensburg (Figs 1 & 2). The landscape surrounding Regensburg is characterized by the presence of four distinct natural landscape units: the Franconian Alb NW of Regensburg; the Bavarian Forest in the NE; the Lower Bavarian Tertiary Hills in the south; and the gently undulating loess-covered broad plain of the Regensburg–Straubing basin, the so-called Dungau (Fig. 1). The geology of the study area is characterized by Cretaceous, Tertiary and Quaternary rocks and deposits. In the Weintinger Holz SE of the study area, an outcrop of Großberger Sandstein, a Cretaceous rock, is present. To the south and west of the study area, Tertiary sediments of the Upper Freshwater Molasse appear, consisting of Höhenhofer Schotter, Tertiary feldspar sands, clays and marl (Oschmann 1958; Unger & Doppler 1996). These cover the Upper Jurassic bedrock of the Franconian Alb, which dips in an eastern and southeastern direction. Quaternary sediments are loess, loess loam and gravels of the Danube. The lower terrace, which is present on both sides of the river, consists of micaceous sands with single gravel interlayers (Oschmann 1958; Buch 1988). In contrast, the gravel of the Rissian high terrace is covered by Würmian loess and loess loam. At the rearward rim of the high terrace, the Lower Bavarian Tertiary Hills border, the Tertiary sediments are also widespread and covered by loess and loess loam. Additionally, Oschmann (1958) mapped alluvial sediments in the area of the investigated fen. The dominant soil types in the study area are Luvisols developed on loess and loess loam, and Cambisols developed on feldspar sands. As a result of the long history of agricultural

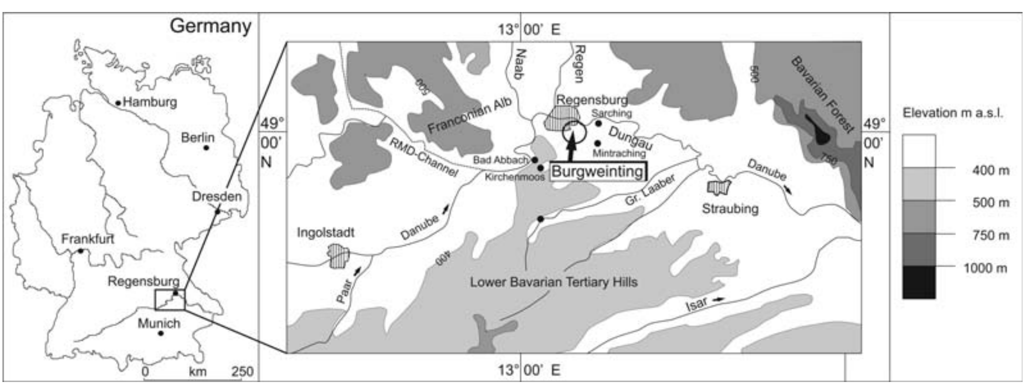


Fig. 1. Location of the study area Burgweinting, situated on the southeastern outskirts of Regensburg. RMD-Channel, Rhein–Main–Donau Channel.

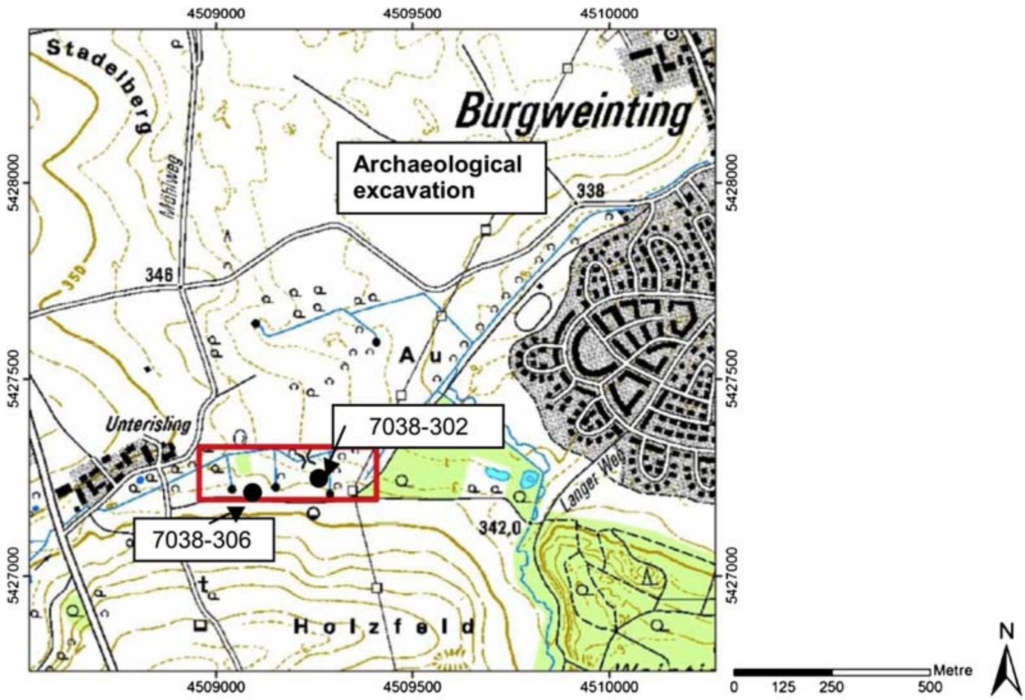


Fig. 2. Study area, Burgweinting. The map shows the location of the archaeological excavation area, the Islinger Mühlbach Fen (rectangle) and the location of the investigated profiles 7038-302 and 7038-306 [base map: topographic map (TK) 1:25 000, Bad Abbach, Bayerisches Landesvermessungsamt 2002].

use, the soil profiles are often truncated and degraded (e.g. Brunnacker 1958; Leopold 2003).

The regional climate of the study area is characterized by its location in the transition zone between oceanic and continental climates. The annual mean air temperature ranges between 7 and 8 °C, and the annual precipitation averages between 650 and 750 mm (BayFORKLIM 1996). The potential natural vegetation in the Lower Bavarian Tertiary Hills would be deciduous woodlands of *Galio–Carpinetum typicum*. Between the merging of the Aubach system into the Danube and the rearward rim of the high terrace to the Tertiary Hills, a *Querco–Ulminetum minoris* would be present (Seibert 1969). However, the study area is an intensively used agricultural landscape, with little woodland cover composed of spruce forests, mixed forests and oak–hornbeam forests. As a result of the land-use pressure caused by building activities and road construction, the area of agricultural land has been reduced.

The Aubach system, a fluvial system that consists of small streams originating in the Lower Bavarian Tertiary Hills, drains the surface towards the Danube. The surface catchment is *c*. 36 km^2 in size. The hydrogeology is determined by the Upper Jurassic bedrock, dipping below the molasse sediments, which represents a continuous aquifer (Bayerisches Landesamt für Umwelt 2007). In the study area, a spring containing small amounts of hydrogen sulphide (H_2S) exists, which was produced by groundwater drilling in 1925.

The study site is a fen [R: 4509000–4509200; H: 5427100; 342 m above sea level (a.s.l.)], located along the Islinger Mühlbach stream (Fig. 2), which will hereafter be referred to as the Islinger Mühlbach Fen. The peat deposit, with a maximum thickness of 5.50 m, has developed in a topogenic depression situated at the southern limit of the high terrace, at the border with the Lower Bavarian Tertiary Hills. The Islinger Mühlbach Fen (*c*. 5.4 ha in size) is classified as a *Kalkniedermoor* (calcareous fen). It is hydrologically fed by mainly carbonate-rich ground water. Oschmann (1958) mapped several sources in the fen area. Additionally, precipitation, surface runoff, and most probably lateral strata water, from the Tertiary sediments, contribute to the water balance. Today, the fen is a protected landscape component, but it was formerly drained by several canals. The Islinger Mühlbach marks the northern boundary of the fen, and the limit of the southern spatial extension of the fen is marked by a track. Analyses of historical maps showed that the Islinger Mühlbach was relocated after the Second World War and the real river course should be *c*. 200 m north of the fen (Raab *et al.* 2008).

According to radiocarbon dating of the bottom peat (profile 7038-302, 337–338 cm, Erl-7516), peat growth commenced during the Late Glacial Period (13408–11878 a cal. BC, 2σ). This is in accordance with comparable ages for the beginning of peat growth from the Kirchenmoos Fen near Poign, *c*. 10 km south of Regensburg (Völkel *et al.* 2002; Raab *et al.* 2005).

Detailed plant macrofossil analyses have been performed on profile 7038-305, derived from the central part of the fen, to study the local mire vegetation. Only a few fen species are identifiable, owing to the high degree of decomposition. Only decay-resistant plant remains, such as plant tissue, rootlets, Amblystegiaceae stems (commonly known as 'brown mosses'), seeds, etc. are present. The major peat constituents are rootlets (*Radizellen*), and therefore the peat is classified as sedge peat. Furthermore, the occurrence of fungal bodies such as *Cenococcum geophilum* indicates periods when the peat surface was well aerated (e.g. Langdon *et al.* 2003). Detailed results are being considered for publication elsewhere.

Archaeological background

An archaeological rescue excavation has been continuing in the *Siedlungskammer* Burgweinting since 1994, conducted by the Office of Archive and Monument Protection of the City of Regensburg (Amt für Archiv und Denkmalpflege der Stadt Regensburg) in co-operation with the Bavarian Office for the Protection of Monuments (Bayerisches Landesamt für Denkmalpflege) (Amt für Archiv und Denkmalpflege 2004). An area of more than *c*. 40 ha has been excavated, and structures and remains from five millennia have been documented (Zuber 2006).

The *Siedlungskammer* Burgweinting is situated on the Rissian high terrace of the Danube, near the edge of the lower terrace. Such locations were preferred settlement sites for millennia because the location between the wet lowland and the wooded hinterland is an effective ecological junction of different natural economic types (Torbrügge 1984; Dallmeier 2004).

Generally, the whole Danube region has been characterized by a constant and relatively dense population since Early Neolithic times (Torbrügge 1984; Paetzold 1992; Dallmeier 2004; Zuber 2006). The earliest remains found in the *Siedlungskammer* Burgweinting belong to the Neolithic Period (5500–2300 or 2200 a cal. BC). The presence of a Neolithic population is evidenced by ceramic shards from the oldest Linear Pottery Culture (sixth millennium BC), *c*. 100 m north of the excavation site (Lüning 1991; Dallmeier 2004). There are single graves from the Corded Ware Culture (third millennium BC) (Kirpal 2005; Zuber 2006), and several graves and settlement evidence from the subsequent Bell Beaker Culture (third millennium BC, End-Neolithic Period) (Schröter 2004; Zuber 2006). The latter finds are interpreted to suggest the existence of small hamlet-like settlements and the first rural population in the *Siedlungskammer* Burgweinting (Zuber 2006). In contrast, the absence of finds for the cultural periods from the End-Neolithic (*c*. 2200 a cal.) to the Urnfield Period (*c*. 1300 a cal. BC, Bronze Age) points to a hiatus in settlement activities (*Siedlungsruhe*) lasting for about 1000 years (Zuber 2006). A remarkably intensive settlement period in the *Siedlungskammer* Burgweinting is the Urnfield Period (1300–800 a cal. BC). An extended Urnfield burial ground with about 400 cremation graves, and traces of two associated villages with a total of 135 post constructions for houses have been excavated so far (Zuber 2002, 2004*a*). These document a *c*. 300 years continuous settlement (Zuber 2006). At the shift from the Urnfield Period to the Iron Age, a decline in population is inferred from the decrease in the numbers of finds. The Iron Age (800–50 a cal. BC) is subdivided into the Hallstatt Period (800–500 a cal. BC) and the La Tène Period (500–50 a cal. BC). For the Hallstatt Period, ditch complexes suggest the presence of so-called *Herrenhöfe*, a characteristic South Bavarian settlement pattern. During the following Early La Tène Age Period the settled area increased again. In the southeastern part of the excavation area, millstones, spindle whorls and *c*. 40 storage pits (*Erdkeller*) are dated to the fourth century BC (Zuber 2004*a*). Bronze slags suggest the processing of bronze in the settlement. The settlement complex was oriented towards the brook rather than to the edge of the terrace (Zuber 2006). For the Middle La Tène Age Period, graves from the fourth century BC were found, and from the Younger La Tène Age Period, remnants of a kiln are present. An immediate succession from the La Tène Period to the oldest Roman settlement is not detectable (Zuber 2006). This is consistent with the archaeological results of the Regensburg region (Schier 1985; Zuber 2006). The Roman Empire is the second prominent settlement period in the *Siedlungskammer* Burgweinting. The development of the rural population in Burgweinting began at the same time as the first Roman military base in Regensburg was established in AD 79, the legionary cohort fort Kumpfmühl (Boos 2004). In

AD 179, under the Emperor Marcus Aurelius, the 'Castra Regina' (fort by the river Regen) was completed for the III Italica Legion in the area of the old town of Regensburg. In Burgweinting, four *villae rusticae* found in an area of *c*. 25 ha attest to a dense population during this time. The self-sustaining *villae rusticae* consisted of residential buildings, stables, barns, storehouses and workshops. Primarily subsistence agriculture was practised, and the troops based at Regensburg and the civilian urban population were provided with the surplus of agricultural products (Moosbauer 2004). Moosbauer (2004) assumed that the area of agricultural land for each *villa rustica* was between 50 and 120 ha, and that the *villae rusticae* in Burgweinting had rather larger areas. The *villae rusticae* were built in the borderland between wet and dry ground on gently inclined slopes. Whereas the pastures and meadows were located in the areas near the stream, the agricultural fields were established uphill. About 20 Roman wells were found near the stream, which served as the source of water. During the 4th century AD, the *villae rusticae* were abandoned, possibly owing to the insecure political circumstances in the border region of *Germania libera* (Zuber 2006). Further settlement of the Burgweinting area is documented for the Early Middle Ages (end of the fifth century AD).

Material and methods

Prior to profile coring, an auger survey of the fen was carried out to find suitable core locations. One location was chosen in the centre of the mire (profile 7038-302), where the disturbance of the peat sequence was expected to be minimal, and the other one at the margin of the fen (profile 7038-306), where the peat has interbedded colluvium layers (peat–colluvia sequence). Profile 7038-302 is in total 455 cm long. It was recovered with a Russian peat corer, which produces undisturbed half-cores (section length 50 cm, diameter 6 cm). The uppermost peat (0–55 cm) was not sampled because this section was disturbed. Profile 7038-306 was gained by percussion drilling (Atlas Copco Co.). The mineral interbeddings in the sequence ruled out coring with a Russian peat corer. The uppermost 50 cm were cored with an open steel drill pipe. The subsequent 2 m were obtained with a closed probe using a Plexiglas tube. Unfortunately, the coring technique caused a compaction of the peat and sediments in the Plexiglas tube and *c*. 50 cm of the tube was empty, although the drilling reached 250 cm in depth. Therefore, the complete sequence is actually 199 cm long.

After recovery, both cores were stored in a cooling chamber at +4 °C until processing. The cores were opened in the laboratory, and the visible stratigraphy was described in terms of changes of colour (Munsell Soil Color Charts, Anon. 1994), peat or sediment composition, carbonate contents and macrofossil remains. The description followed Ad-Hoc AG Boden (2005) and the Troels–Smiths sediment description system was used (see Birks & Birks 1980). Prior to sampling, the profiles were documented by digital photography.

The profiles were sectioned into continuous 1 cm slices (bulk samples). From the centre of each slice, a 1 cm^3 subsample was extracted for potential pollen analyses. Additionally, macro-remains samples were collected for species determination and radiocarbon dating. All samples were dried in a laboratory-type drying cabinet at +40 °C. For the analyses, one part of the bulk sample was carefully crushed using a mortar, and the other part was pulverized using a bullet mill. To characterize major variations in peat stratigraphy, geochemical analyses were conducted on both profiles. The analyses were carried out at 1 cm intervals. Geochemical analyses on profile 7038-302 were carried out from 57 to 454 cm depth, but only the results from 57 to 225 cm depth are given in this paper. Profile 7038-306 was analysed from 51 to 164 cm depth.

The determination of total carbon, nitrogen and sulphur contents, sequential loss on ignition and colorimetric humification were carried out on the ground bulk samples. Total carbon (wt%), total nitrogen (wt%) and total sulphur (wt%) were determined with a CNS auto-analyser (Vario EL III, Elementar Analysensysteme GmbH). The sequential determination of loss on ignition (LOI) was carried out to estimate organic matter values (OM), $CaCO_3$ and ignition residue following the recommendations of Heiri *et al.* (2001). For that, 0.25 g homogenized bulk samples (duplicates) were sequentially combusted at 550 °C (OM) and 950 °C ($CaCO_3$). For the calculation of the proportion of organic carbon (C_{org}), the percentage of OM is divided by two, as it is assumed that the proportion of organic carbon is roughly 50% of the OM (Ad-Hoc AG Boden 2005). The proportion of $CaCO_3$ is calculated by multiplying the loss on ignition after combustion at 950 °C by a factor 1.36. Finally, the ignition residue is calculated according to Lawson *et al.* (2004). The determination of colorimetric humification was exclusively performed on profile 7038-302 for the segment from 57 to 344 cm depth according to a laboratory protocol slightly modified from Chambers (2006). The samples were treated with an alkali extraction procedure (NaOH 6%). Afterwards, the transmission (expressed as percentage transmission, TM %) of the solution was measured at a wavelength of 540 nm on a spectral photometer (Lambda

25 UV/VIS Perkin Elmer). High TM values correspond to slightly humified peat, and low TM values to highly humified peat.

For microscopic charcoal analyses, the method described by Rhodes (1998) was chosen, because this is a gentle processing method in which little particle fragmentation occurs. Several test runs showed that, after preparation of sample material from profile 7038-302, the abundant material in the Petri dishes hindered the counting of the charcoal particles. Therefore, the sample size was reduced to 0.1 g. In contrast, the test runs of profile 7038-306 showed that a sample size of 0.2 g was acceptable and therefore this sample size was used. Counting of the microscopic charcoal particles was carried out with a stereo binocular microscope (Zeiss Type 475052-9901, Zeiss Stemi DV4) with incident light at 20–40× magnification, using a manufactured grid (1 cm × 1 cm) for orientation. The samples were completely counted, but not identified. All particles with the characteristic attributes (black, completely opaque, angular, with a silvery lustre in incident light) were counted as charcoal fragments (Swain 1978; Patterson *et al.* 1987; Clark 1988; Rhodes 1998; Enache & Cumming 2006). For the comparison of the results, the absolute counts were converted to parts per gram (ppg). The pre-examination of the samples in the Petri dishes, which involved measuring the longitudinal axis of the fragments with a micrometre eyepiece, showed that the fraction sizes of the charcoal particles and the fraction size distribution differ in the two profiles, and therefore different counting strategies were applied. In total 75 samples from profile 7038-302 were analysed at 1 cm intervals. Additionally, the section from 82 to 69 cm depth was continuously counted. The microscopic charcoal particles of this profile were classified into three classes of 50–500, 500–1000 and >1000 μm. From profile 7038-306, the microscopic charcoal analyses were conducted for the section from 51 to 164 cm depth, at 1 cm intervals ($n = 55$). No analyses were carried out on the samples from 155–156 and 113–114 cm, because the sample size was too small. The microscopic charcoal particles of this profile were classified into the classes of 50–150, 150–250 and >250 μm. Finally, for each profile the microscopic charcoal sum was calculated.

For chronological control, a total of 10 ^{14}C samples (wood fragments, undetermined plant macro-remains and peat bulk samples) were selected from profiles 7038-302 and 7038-306 for ^{14}C-AMS (accelerator mass spectrometry) dating at the AMS C14-Labor Erlangen of the Friedrich-Alexander-Universität Erlangen–Nürnberg. The ^{14}C dates were converted to calibrated ages (a cal. BC or AD) using the calibration dataset of Reimer *et al.* (2004).

Results and interpretation

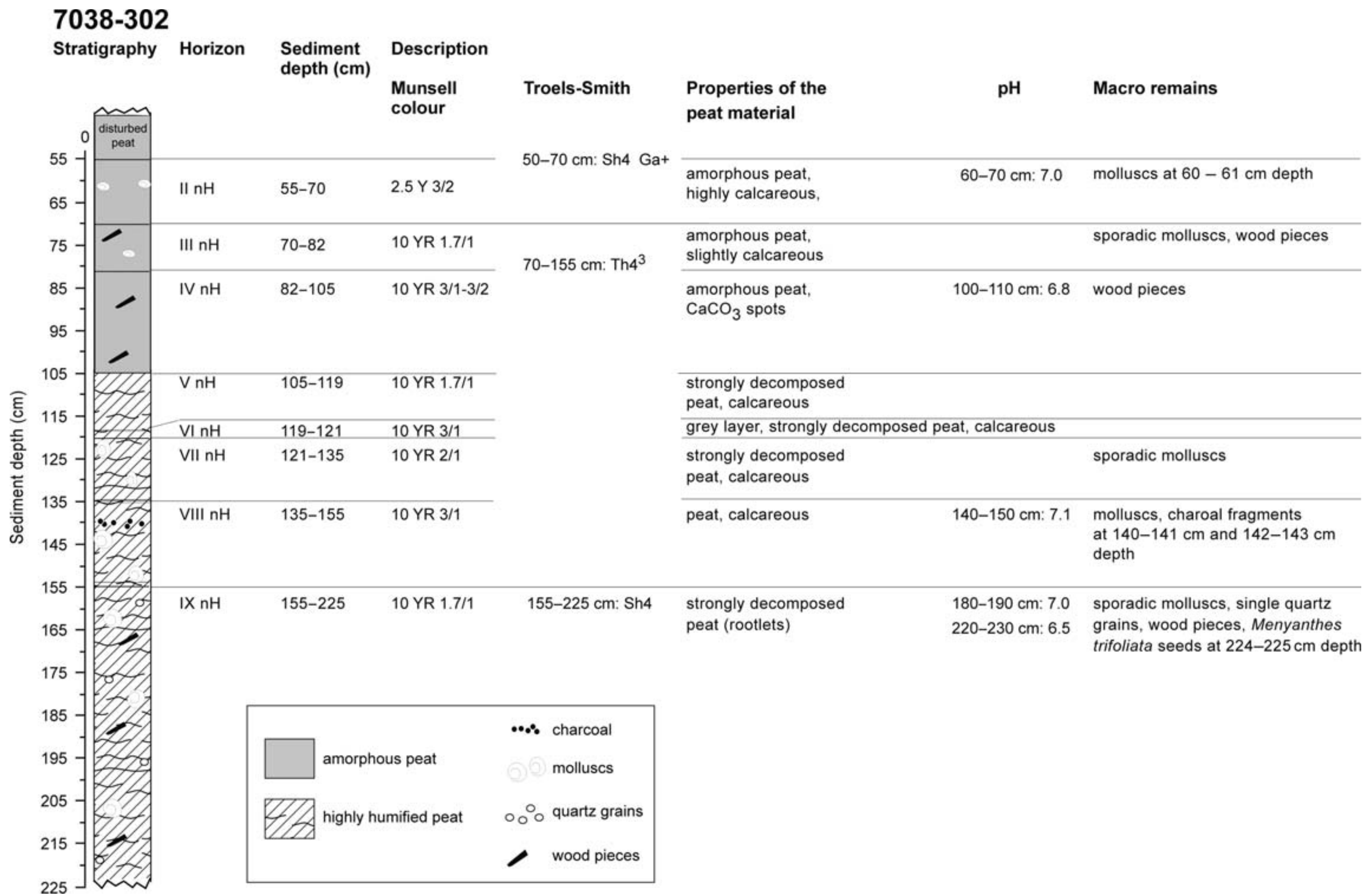
Stratigraphy and geochemistry of profile 7038-302

The peat profile 7038-302 from the centre of the fen (Fig. 2) is in total 455 cm long and can be visually subdivided into three units. The first unit is loess at the base (455–361 cm depth). This is overlain by a transition horizon from loess to peat (361–341 cm depth), which represents the second unit. The third unit is a 286 cm thick minerotrophic peat (341–55 cm depth), which includes an interbedded mineral layer at 329–322.5 cm. The peat from 55 to 0 cm depth was not sampled, because it was disturbed. This study focuses on the peat from 225 to 55 cm depth, as it was expected to include the settlement periods. A detailed profile description of this section is shown in Figure 3.

The minerotrophic peat has a brownish black to black colour and is amorphous to highly humified, and hence only few plant macro-remains are present and identifiable. The peat is mainly composed of rootlets and is therefore classified as sedge peat. Wood fragments are present, which are often strongly decomposed. At 224–225 cm depth, some seeds of *Menyanthes trifoliata* were found, indicating wet conditions and mineral enrichments (Blundell *et al.* 2008). Furthermore, charcoal fragments and mollusc shells are present (Fig. 3). The peat is moderately to highly calcareous and carbonate precipitates are visible in some sections of the peat. This resulted in pH values between 6.5 and 7.1 and indicates slightly acidic to neutral conditions (Ad-Hoc AG Boden 2005). Based on the geochemical data (total carbon (TC) wt%, total nitrogen (TN) wt%, total sulphur (TS) wt%, TM %, C_{org}/TN ratio, organic matter (OM) wt%, $CaCO_3$ wt%, ignition residue wt%), the peat from 255 to 55 cm depth is subdivided into eight sections (Fig. 4).

Section 8 (225–198 cm). The peat is characterized by relatively high TC (39.8–46.7 wt%), TN (1.9–2.4 wt%) and TS (3.5–5.3 wt%) values. The C_{org}/TN ratio is between 17.8 and 23.0. The TM values range between 26.8 and 54.2%. The OM values are high (73.9–85.9 wt%). The $CaCO_3$ values are between 0.7 and 8.1 wt%, with increasing values towards the top. The proportions of the ignition residue of 12.9–17.7 wt% are comparatively low and run parallel to the $CaCO_3$ curve.

Section 7 (198–184 cm). The TC (29.4–41.5 wt%), TN (1.5–2.2 wt%) and TS (2.2–4.2 wt%) values decrease towards the top. The C_{org}/TN ratio (14.4–17.7) is lower than in Section 8. The TM values (41.3–60.8%) increase towards the top,



Horizon	Sediment depth (cm)	Munsell colour	Troels-Smith	Properties of the peat material	pH	Macro remains
II nH	55–70	2.5 Y 3/2	50–70 cm: Sh4 Ga+	amorphous peat, highly calcareous,	60–70 cm: 7.0	molluscs at 60 – 61 cm depth
III nH	70–82	10 YR 1.7/1	70–155 cm: Th4[3]	amorphous peat, slightly calcareous		sporadic molluscs, wood pieces
IV nH	82–105	10 YR 3/1-3/2		amorphous peat, $CaCO_3$ spots	100–110 cm: 6.8	wood pieces
V nH	105–119	10 YR 1.7/1		strongly decomposed peat, calcareous		
VI nH	119–121	10 YR 3/1		grey layer, strongly decomposed peat, calcareous		
VII nH	121–135	10 YR 2/1		strongly decomposed peat, calcareous		sporadic molluscs
VIII nH	135–155	10 YR 3/1		peat, calcareous	140–150 cm: 7.1	molluscs, charoal fragments at 140–141 cm and 142–143 cm depth
IX nH	155–225	10 YR 1.7/1	155–225 cm: Sh4	strongly decomposed peat (rootlets)	180–190 cm: 7.0 220–230 cm: 6.5	sporadic molluscs, single quartz grains, wood pieces, *Menyanthes trifoliata* seeds at 224–225 cm depth

Fig. 3. Profile 7038-302; stratigraphy, horizons and description from profile depth 225 to 55 cm.

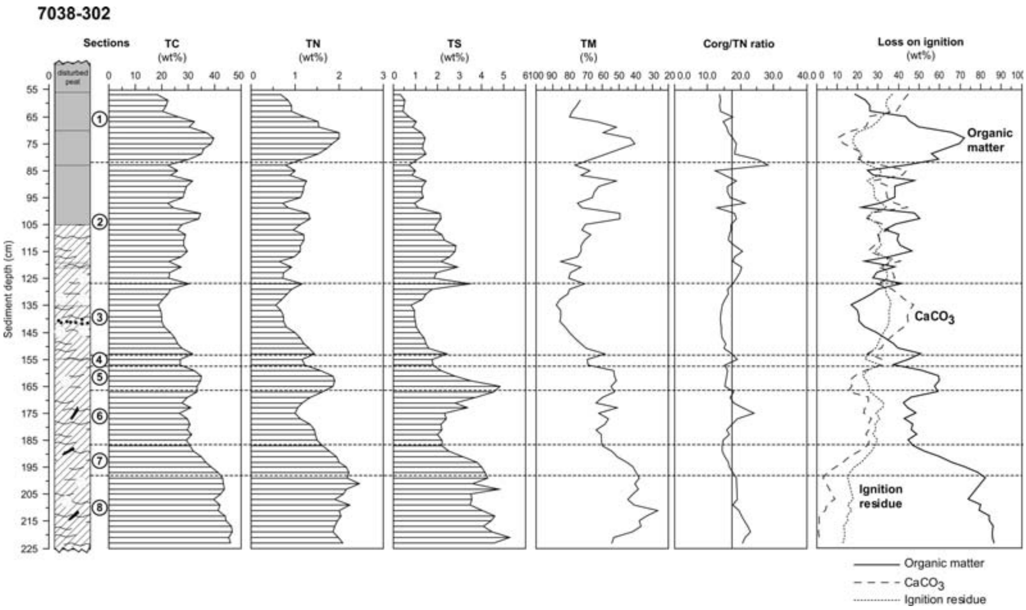


Fig. 4. Profile 7038-302; geochemical parameters (TC, TN, TS, TM, C_{org}/TN ratio, loss on ignition) and sections distinguished (1–8).

whereas the OM values (44.7–74.7 wt%) decrease in the same direction. Both $CaCO_3$ (5.2–25.7 wt%) and ignition residue values (16.3–29.5 wt%) increase towards the top.

Section 6 (184–168 cm). Whereas the TC values (27.7–31.4 wt%) show only minor fluctuations, TN (1.0–1.5 wt%) decreases towards the middle part of this section, and then increases towards the top. TS (2.0–3.7 wt%) initially remains at about 2.0 wt%, and then increases towards the top. The C_{org}/TN ratios are between 15.9 and 24.0, with a maximum at 175–176 cm depth. The TM values fluctuate between 56.6 and 64.0%. OM varies between 42.6 and 49.0 wt%. The $CaCO_3$ (22.7–26.6 wt%) and ignition residue (27.2–32.5 wt%) contents run parallel and show only minor fluctuations.

Section 5 (168–158 cm). The TC (32.3–35.2 wt%) and TN (1.6–1.9 wt%) values are higher than in Section 6. TS (2.2–4.9 wt%) shows a peak at 165–166 cm depth, which is followed by decreasing values. The C_{org}/TN ratio is between 15.3 and 18.0. The TM values are between 51.6 and 55.2%, and the OM contents are between 51.3 and 59.9 wt%. The $CaCO_3$ values of 15.1–23.7 wt%, and the ignition residue of 22.2–25.7 wt% are lower than in Section 6, and also run parallel to each other.

Section 4 (158–154 cm). This 4 cm thick section has lower values of TC (27.2–27.3 wt%), TN (1.2 wt%) and TS (1.8 wt%). The C_{org}/TN ratio is between 15.3 and 19.0. The TM value is higher (68.6–69.5%) than below. The OM decreases sharply (37.3–45.2 wt%), whereas the $CaCO_3$ (31.3–32.2%) and ignition residue (23.4–30.5%) show higher values.

Section 3 (154–128 cm). The TC (18.7–31.7 wt%), TN (0.6–1.5 wt%) and TS (0.8–2.5 wt%) decrease towards the middle part, and then increase towards lower profile depths. The C_{org}/TN ratio (14.0–17.4) maintains low values. The TM values rise strongly (58.8–87.9%) towards the middle part of this section, as do the OM values (16.9–50.6 wt%). In contrast, $CaCO_3$ (24.5–46.9 wt%) increases towards the middle part, as do the values for ignition residue (24.9–36.1 wt%), which run parallel to $CaCO_3$, but are less pronounced.

Section 2 (128–84 cm). All geochemical parameters show highly fluctuating values. The TC values are between 23.0 and 34.8 wt%, and TN values are between 0.7 and 1.4 wt%. The TS values (0.9–3.5 wt%) show a decrease towards the top. The C_{org}/TN ratios vary between 12.4 and 21.6. The variations in TM are also high (49.7–85.6%). The OM values range between 22.0 and 50.4 wt%. $CaCO_3$ (24.2–43.4 wt%) and ignition residues (24.5–36.1 wt%) values also show high fluctuations.

Section 1 (84–55 cm). TC (22.5–39.7 wt%) and TN (0.8–2.0 wt%) values rise towards the middle part of this section and then show a decrease. The decline in TS (0.8–1.5 wt%) values continues. The C_{org}/TN ratio (14.9–28.5) shows a peak at 83–84 cm. The TM values range between 40.5 and 80.0%, with the highest values in the middle part of the section. The OM values (43.6–72.1 wt%) also are highest in the middle part of the section. In contrast, $CaCO_3$ (10.2–30.1 wt%) and ignition residue (17.5–31.3 wt%) decrease towards the middle part and increase towards the top. The uppermost part of the profile, at <65 cm depth, has decreasing values for TC (22.5–18.4 wt%), TN (0.7–0.9 wt%) and TS (0.5–0.4 wt%). The C_{org}/TN ratio (13.7–14.0) is low. The TM values are between 73.8 and 78.5%. The OM values (18.8–26.0 wt%) decrease, whereas the $CaCO_3$ values (38.4–44.3 wt%) and ignition residues (33.7–36.8 wt%) increase. Most probably this uppermost profile section has been disturbed by humans in the form of past drainage measures and use as a meadow.

The results of the analyses of the geochemical parameters are highly variable throughout the peat profile, suggesting changing peat compositions and peat formation conditions. The TC values throughout the profile are between 18.4 and 46.7 wt%. The TN values in the peat profile are between 0.6 and 2.5 wt% with the highest values at 191–224 cm, 166–161 cm and 78–73 cm, which could suggest an altered peat composition. Overall, the TN values are typical for minerotrophic peat (see Grosse-Brauckmann 1990). The TS values are between 0.4 and 5.3 wt% and reach a maximum for the profile in the bottom section at 224–193 and 168–165 cm. Between 165 and 135 cm, with the exception of a small peak at 155 cm, the TS values decrease. From 135 to 105 cm, the TS values show an increase. From 105 cm to the top of the profile, TS values decrease. The TS values represent pyrite-bound S, as pollen and macrofossil analyses have shown that pyrite framboids (FeS_2) are present in pollen grains and plant tissue. The sulphur is derived from organic decay and most probably from the groundwater. The C_{org}/TN ratios vary between 12.4 and 28.5 and are typical for minerotrophic fen peat (Grosse-Brauckmann 1990). Close C_{org}/TN ratios indicate strong decomposition and decay of organic material under relatively anaerobic conditions. Colorimetric humification (TM %) was ascertained for peat stratigraphic investigation. The TM values fluctuate throughout the profile. The TM values run parallel to the organic matter curve. Therefore, highly humified peat corresponds to high organic matter contents and vice versa. The different degrees of humification might reflect the conditions during peat formation; however, the humification is also influenced by the decay resistance of the peat-forming plants (Yeloff & Mauquoy 2006).

The organic matter (OM), $CaCO_3$ and ignition residue values are determined by sequential LOI. The OM values are highly variable, between 16.9 and 86.4 wt%. The calcium carbonate ($CaCO_3$) values of the peat are between 0.7 and 46.9 wt%, and prove that the peat is generally highly calcareous. $CaCO_3$ values of <1 wt% are present only in the lower part of the profile at 224–213 cm depth. Carbonate precipitates, the so-called *Almkalk* (synonyms are *Wiesenkalk* or *Wiesenmergel*) are visible in the peat. Carbonate precipitation is related to spring water rich in calcium bicarbonate (Jerz 1983; Grosse-Brauckmann 1990; Niller 1998). Additionally, a minor proportion of $CaCO_3$ comes from mollusc shells. The ignition residue throughout the peat profile is between 12.9 and 36.8 wt%, and therefore is comparatively high. According to Grosse-Brauckmann (1990) the ash contents of common minerotrophic peat are between 5 and 15 wt%. The ignition residue represents the contents of mineral components, which are primarily silicates in the form of easily transportable grain-size fractions of silt and clay. Horizontally and vertically moving groundwater is linked with the transport of allochthonous material in a dissolved state. Mineral input by surface runoff may deliver further material. The $CaCO_3$ and the ignition residue depth curves show coinciding variabilities, suggesting a relationship between $CaCO_3$ and ignition residue. Overall, both parameters reflect the geochemistry of the carbonaceous groundwater connected with the input of minerals.

Stratigraphy and geochemistry of profile 7038-306

Profile 7038-306 is from the margin of the fen (Fig. 2). The peat–colluvia sequence is 199 cm long and shows a complex stratigraphy. Percussion drilling of the core caused an artificial compaction of the material (see Methods).

The peat–colluvia sequence is built up by loess at the base (199–180 cm), which is overlain by loess loam (180–159 cm). A transition horizon from loess loam to peat is present at 159–152 cm. This is followed by amorphous to highly humified peat, composed of herbaceous plants with some wood fragments (152–117 cm). From 117 to 68 cm depth, the profile was subdivided into three peat–colluvium complexes (117–100, 100–95 and 95–68 cm). A 3 cm thick peat–colluvium transition horizon at 68–65 cm depth leads to the 65 cm colluvial cover on top of the sequence. A detailed profile description is shown in Figure 5.

For the profile at 164–51 cm depth, the following geochemical parameters were established: TC (wt%), TN (wt%), TS (wt%), C_{org}/TN ratio, OM (wt%), $CaCO_3$ (wt%), and ignition residue (wt%), and the profile was subdivided into eight sections accordingly (Fig. 6).

Section 8 (199–159 cm). The loess at the base (199–180 cm) is covered by loess loam (180–159 cm). Geochemical analyses were carried out from a 164 cm profile depth towards the top, and therefore are available for the upper part of the loess loam only. TC values (3.6–3.7 wt%) and TS values (0.1–0.4 wt%) are low, whereas the TN proportions (3.2–3.7 wt%) are comparatively high. The C_{org}/TN ratio is 1.3–1.4. The OM values of 9.0–9.3 wt% and the $CaCO_3$ values (1.9–2.8 wt%) are low. In contrast, the ignition residue values (87.8–89.0 wt%) are very high.

Section 7 (159–152 cm). This is the transition horizon from the mineral substrate to peat. The TC values (4.9–8.6 wt%) are relatively low. The TN values are between 2.5 and 3.2 wt%. The TS values are below <1 wt%. The C_{org}/TN ratios (2.4–2.7) result from the low OM values and indicate a high degree of decomposition. The substrate becomes increasingly rich in OM (11.9–17.5 wt%) towards lower profile depths. The $CaCO_3$ values (2.9–3.1 wt%) are low. The substrate is mainly mineral, as indicated by the high amount of ignition residue (79.8–85.2 wt%). Towards the top, the ignition residues show a strong decrease.

Section 6 (152–117 cm). This 34 cm thick peat shows TC values that increase at the bottom (13.2–46.2 wt%) and remain high overall. The TN values (2.6–7.8 wt%) are highly variable, ranging around 3 and 4 wt%. Noticeably higher TN values of 6–8 wt% are measured in the profile section from 131 to 117 cm depth, with the exception of one sample at 123–124 cm depth with 2.6 wt%. The TS values (0.4–3.2 wt%) also show an increase towards lower profile depths. The range of variation of the C_{org}/TN ratios (4.5–16.1) is wide and is contrary to the TN curve shape. The OM (25.7–85.6 wt%) values sharply increase and remain high throughout this peat section. The $CaCO_3$ values (0–3.0 wt%) are low. The ignition residues (13.9–71.4 wt%) decrease and then remain at a lower level throughout the profile.

Section 5 (117–100 cm). The TC (21.8–35.0 wt%), TN (1.5–2.5 wt%) and TS (0.4–1.4 wt%) values decrease. The C_{org}/TN ratios fluctuate between 7.0 and 15.3. The OM values (30.2–67.0 wt%) decrease towards lower profile depths, whereas $CaCO_3$ (1.8–3.7 wt%) remains at a low level. In contrast, ignition residue (30.0–66.4 wt%) increases towards lower profile depths. The analyses show that the substrate is composed of organic and mineral substrates in approximately equal parts.

Section 4 (100–95 cm). The TC (8.8–20.5 wt%), TN (0.6–1.5 wt%) and TS (0.1–0.3 wt%) values decrease towards lower profile depths. The C_{org}/TN ratios (13.5–14.6) are stable. OM values (18.4–40.0 wt%) decrease, whereas the ignition residues (57.7–80.3 wt%) sharply rise. The $CaCO_3$ values (1.3–2.0 wt%) are low. The analyses show that this part of the profile is mainly composed of mineral substrate mixed with organic material.

Section 3 (95–68 cm). The TC contents are between 11.0 and 21.8 wt%. The TN contents are low (generally less than 2%), with the exception of one sample at 71–72 cm with 5.6 wt%. The TS values (0.1–0.2 wt%) are generally low. The C_{org}/TN ratio is about 15, except in the layer with increased TN where the C_{org}/TN ratio is four. The OM values fluctuate (22.5–44.6 wt%), as do the ignition residue values (52.6–76.0 wt%). The $CaCO_3$ (1.4–2.9 wt%) is low. The analyses show that this section is mainly composed of mineral material with a higher proportion of organic matter than below, and that the proportions of mineral substrate and organic matter alternate.

Section 2 (68–65 cm). This section represents the transition from organic-rich mineral substrate to the colluvial cover. The TC (8.7–12.6 wt%), TN (0.6–0.8 wt%) and TS (0.1–0.2 wt%) values decrease. The C_{org}/TN ratios are between 15.2 and 16. OM values are between 17.9 and 25.5 wt%, and the ignition residue is high (72.6–80.4 wt%). The $CaCO_3$ (1.7–1.9 wt%) values are low.

Section 1 (65–50 cm). This section is the lowermost part of the colluvial cover. The TC (0.7–2.0 wt%) and TN (0.1–0.2 wt%) values are low. TS was not detected in this sediment. The C_{org}/TN ratios are between 16.5 and 36.1. The OM (3.4–6.2 wt%) values are low, as are the $CaCO_3$ values (1.7–3.1 wt%). In contrast, the ignition residues rise sharply (92.4–95.6 wt%). The geochemical parameters show that the substrate is mainly composed of mineral material with a small amount of organic material.

In conclusion, the results of the geochemical analyses are consistent with the stratigraphic description of the sequence. The total carbon contents (TC) consist mainly of organic carbon, as shown by the high OM values. $CaCO_3$ contributes only minimally to the TC contents, as the values are low. The TN values fluctuate throughout the

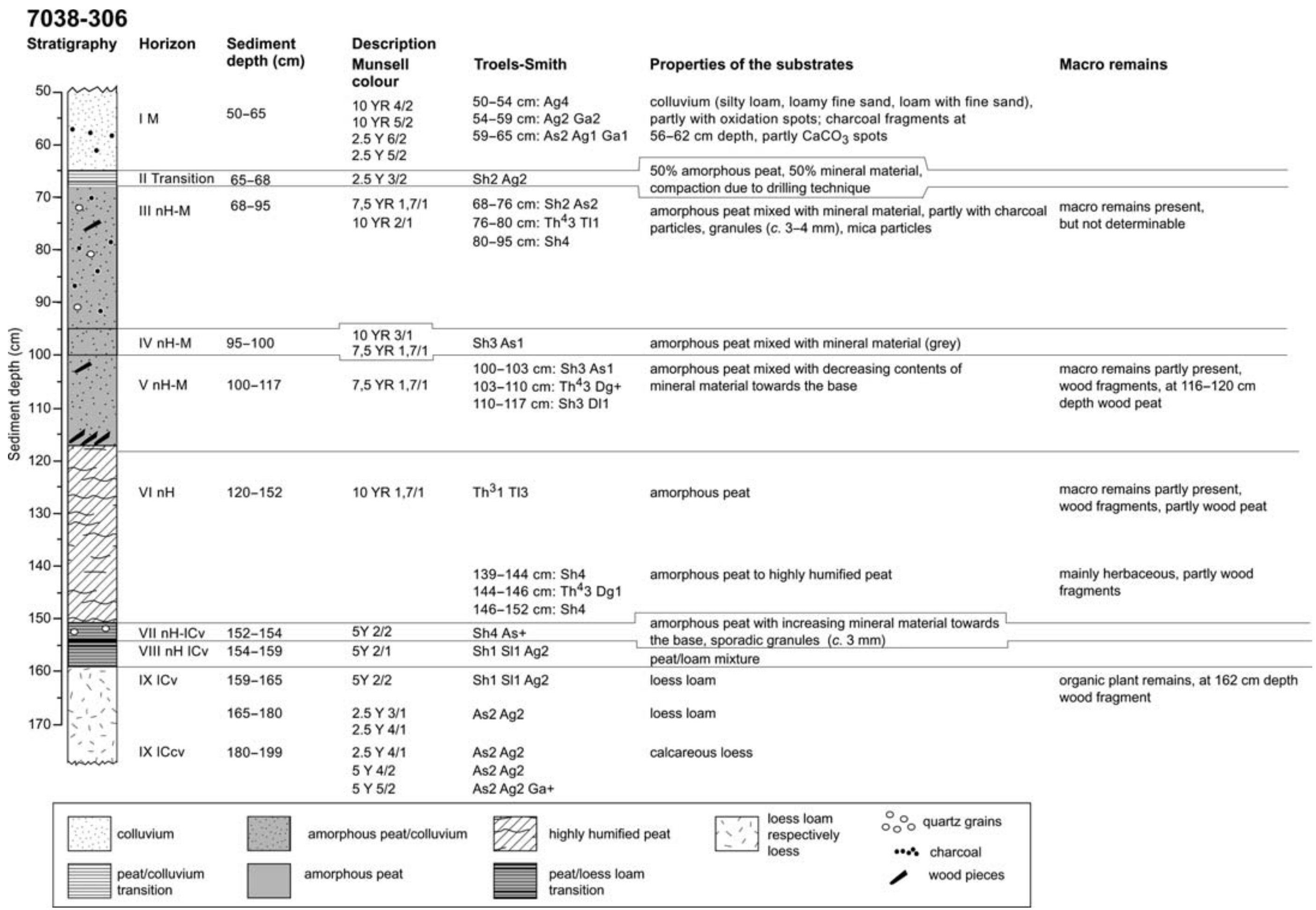


Fig. 5. Profile 7038-306; stratigraphy, horizons and description from 199 to 50 cm profile depth.

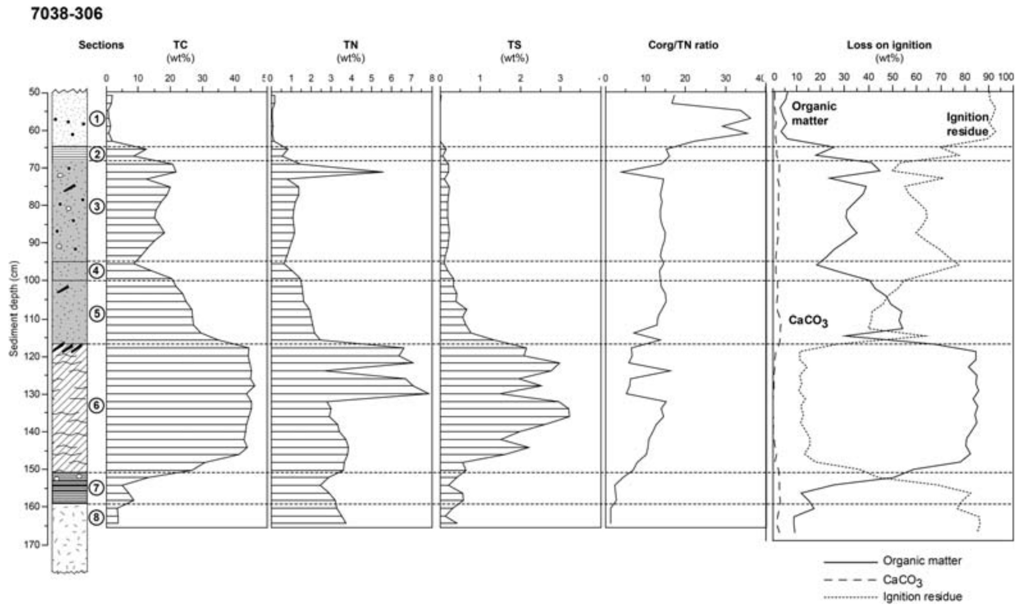


Fig. 6. Profile 7038-306; geochemical parameters (TC, TN, TS, C_{org}/TN ratio, Loss on ignition) from 164 to 50 cm profile depth and sections distinguished (1–8).

profile, but are exceptionally high at the 131–117 cm and 71–72 cm profile depths. These high TN percentages could result either from nitrogen-rich plants or from anthropogenic nitrogen input. The TS percentages are highest in the peat section (Section 6), and they show that pyrite-forming conditions (anaerobic conditions, S and Fe availability) were present in this section. The C_{org}/TN ratios are highly variable throughout the profile. The widest range in C_{org}/TN occurs in Section 1 as a result of very low TN and low OM percentages in the mineral substrate. In general, the proportions of OM and ignition residues reflect the profile stratigraphy. From 117 cm depth to the top, changing proportions of OM and ignition residue indicate peat development with colluvial interbeddings. Three peat–colluvium layers (117–100, 100–95 and 95–68 cm depth) can be determined based on varying proportions of organic matter and mineral substrate. However, as a result of the artificial compaction caused by the drilling technique, distinct colluvial layers cannot be distinguished.

Microscopic charcoal analyses

Microscopic charcoal analyses of profile 7038-302 were conducted exclusively on the peat substrate (193–57 cm profile depth). Charcoal particles are continuously present throughout the profile in variable quantities. The minimum microscopic charcoal particle sum is 219 ppg and the maximum is 29 435 ppg (mean: 7700 ± 4977 ppg). The charcoal fragments were subdivided into three size classes: 50–500 μm, 500–1000 μm and >1000 μm. In addition, the total sum of microscopic charcoal particles was calculated (Fig. 7). The particle size classification shows that the majority of the particles belong to the small size class of 50–500 μm (219–28 647 ppg), followed by the medium size class of 500–1000 μm (0–1671 ppg). Furthermore, large particles >1000 μm (0–199 ppg) are also present (Fig. 7). The depth curves of the small and medium size fractions show approximately comparable shapes, whereas the depth curve of the large particle fraction has a different shape.

Based on the curve shape of the microscopic charcoal sum, nine fire episodes (FE 1–9) have been identified. The lowermost profile section (193–164 cm) is defined as FE 1, with comparatively low microscopic charcoal counts. In the next section (164–145 cm), noticeably higher microscopic charcoal counts are present and this section is therefore classified as FE 2. Between 145 and 132 cm, the microscopic charcoal counts are at a lower level (FE 3). The profile section from 132 to *c.* 98 cm (FE 4) is a segment with relatively high microscopic charcoal particle counts extending over a *c.* 34 cm long section, with a peak at 115–116 cm. Between *c.* 98 and 79 cm (FE 5) the charcoal counts tend to decrease, but vary in quantity. FE 6 (79–76 cm) represents a 3 cm thick layer with increased counts and a peak at 78–77 cm.

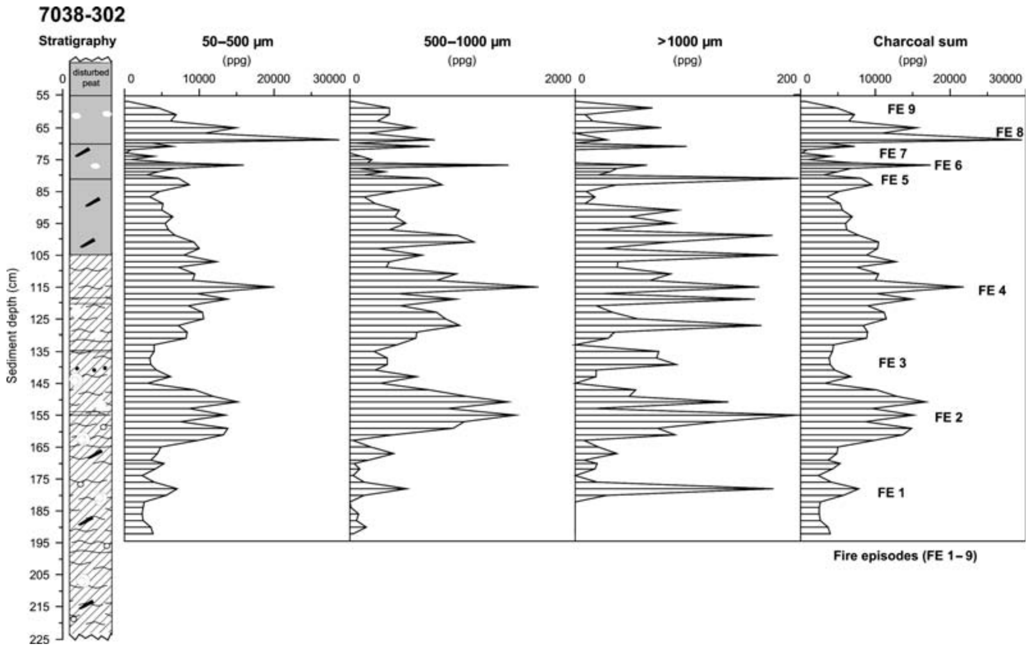


Fig. 7. Charcoal record of profile 7038-302, which shows the different charcoal size classes: 50–500 µm (ppg), 500–1000 µm (ppg), >1000 µm (ppg) and the charcoal sum (ppg).

From 76 to 71 cm, the lowest charcoal particle abundance throughout the profile was found (FE 7). In the section from 71 to 64 cm (FE 8) the microscopic charcoal counts increase, with the highest counts throughout the profile at 70–69 cm. From 64 to 57 cm the microscopic charcoal counts decrease towards the top of the profile (FE 9).

On profile 7038-306, microscopic charcoal analyses were undertaken on the three substrate types of loess, peat and colluvial material (profile section 164–51 cm depth). Microscopic charcoal particles are present throughout the profile. The minimum charcoal sum is 173 ppg and the maximum 5576 ppg (mean: 1153 ± 1123 ppg). The microscopic charcoal fragments were subdivided into three size classes: small (50–150 µm), medium (150–250 µm) and large (>250 µm) (Fig. 8). The dominant particle class is the small particle size fraction with 137–4263 ppg. This is followed by the medium size fraction with 5–865 ppg, and then the large fraction with 0–783 ppg.

Based on the shape of the charcoal sum depth curve, seven fire episodes (FE 1–7) are identifiable. FE 1 corresponds to the profile depth from 164 to *c.* 151 cm. Initially, there is an increase in charcoal abundance up a depth of 154–153 cm, followed by a decrease in abundance. The profile section between 153 and 145 cm is classified as FE 2, with the highest microscopic charcoal abundance throughout the profile. In the section from 145 to 127 cm depth (FE 3) considerably lower numbers of charcoal fragments were counted. The next section, between 127 and 119 cm depth (FE 4), contains even lower numbers of charcoal fragments than FE 3. In the section from 119 to 105 cm depth (FE 5), the charcoal counts increase slightly. Subsequently, in the section from 105 to 87 cm depth (FE 6), the microscopic charcoal counts are low. In the section from 97 to 51 cm, the charcoal fragments are again frequent (FE 7), and at almost the same level as in FE 3.

The two charcoal records show several similarities as well as discrepancies. Beginning with the similarities, microscopic charcoal is commonly recorded in both profiles, and therefore documents the occurrence of fire in the environment. The shapes of the curves of the microscopic charcoal sums and the varying abundance of charcoal fragments indicate a continuous but alternating fire history.

With respect to the discrepancies in the charcoal records, there are four major aspects to discuss. The first aspect concerns the different core locations within the Islinger Mühlbach Fen, which resulted in different sequences of stratigraphy and furthermore, in different fire records. The different core locations and substrates also involve different transport and deposition processes. Although the

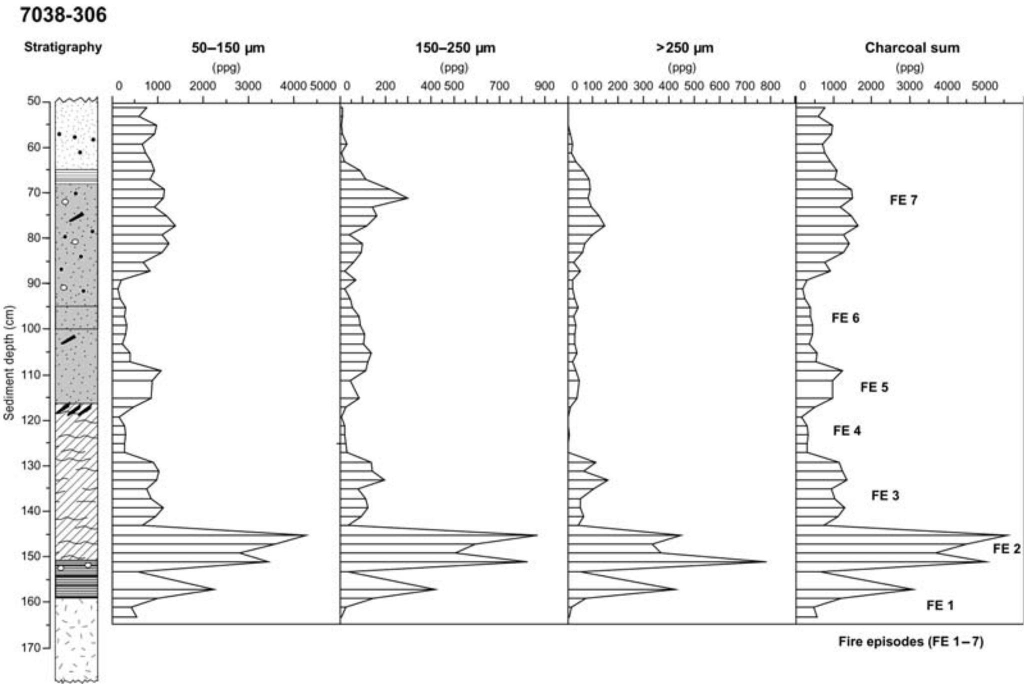


Fig. 8. Charcoal record of profile 7038-306, which shows the different charcoal size classes: 50–150 µm (ppg), 150–250 µm (ppg), >250 µm (ppg) and the charcoal sum (ppg).

charcoal particles of the central profile most probably derive from aerial transport, the marginal profile can also include charcoal transported surficially by water and/or charcoal incorporated into colluvial material. Both terrestrial transport processes allow a secondary redeposition of charcoal fragments. Furthermore, a disintegration of larger charcoal particles by saltation is possible, as charcoal is brittle. This would also explain the absence of larger charcoal fragments in profile 7038-306 from the margin of the fen. The second aspect concerns the abundance of charcoal particles, which is much higher in the centre of the fen (7038-302) than in the peat–colluvia sequence at the margin (7038-306). The central site probably represents an integrating sink for both regional and local charcoal input, thus receiving more total charcoal. The third aspect concerns the different charcoal particle sizes and the size-class distribution. There is a long-standing discussion about charcoal particle sizes and their interpretation with respect to transport distance (e.g. Clark *et al.* 1998; Froyd 2006). It is generally assumed that the aeolian transport of larger particles is possible only over short distances (Patterson *et al.* 1987; Clark 1988), and that small particles, transported over long distances, indicate fire at regional or intercontinental sources (Clark 1988). Both charcoal records are dominated by small particles, suggesting charcoal particles from aerial fallout, and therefore reflecting the regional fire history. However, there are also larger particles in the record of profile 7038-302, which hint at burning of local biomass, such as the probable burning of local mire vegetation. Although the charcoal particles were not identified, a large number appear to derive from herbaceous plants, which supports this assumption. Finally, the most striking aspect is the different charcoal depth curves of the profiles. Therefore, both fire records have to be evaluated with consideration of the chronological information.

Chronology

The chronology of the peat profiles is based on 10 ^{14}C AMS ages. The radiocarbon ages, the analysed materials, and δ^{13}C (‰) values are presented in Table 1. The calibrated radiocarbon ages (a cal. BC or AD, 2σ confidence interval) are correlated to the chronozones as defined by Mangerud *et al.* (1974).

In general, the five ^{14}C ages from profile 7038-302 show a consistent succession from older to younger ages with movement from greater depth to the top. At a depth of 153–152 cm, an age of 6426–6236 a cal. BC (2σ, Erl-13006) was

Table 1. *Radiocarbon ages from the Islinger Mühlbach Fen sequences*

Sample depth (cm)	Laboratory code	Horizon	Material analysed	^{14}C a BP (1σ)	a cal. BC or AD (2σ)	$\delta^{13}C_{PDB}$ (‰)	Chronozone
Profile 7038-302							
74–75	Erl-7289	III nH	Wood	3478 ± 44	1916–1687 BC	−30.6	MSB
91–92	Erl-7290	IV nH	Wood	3551 ± 46	2017–1745 BC	−31.2	MSB
112–113	Erl-11878	V nH	Plant remains	6663 ± 50	5562–5491 BC	−26.9	MA
116–117	Erl-11879	V nH	Plant remains	6931 ± 49	5971–5723 BC	−26.0	EA–MA
152–153	Erl-13006	VIII nH	Bulk peat sample	7461 ± 52	6426–6236 BC	−27.4	EA
Profile 7038-306							
78–79	Erl-11886	III nH-M	Bulk sample	1988 ± 43	94 BC–123 AD	−28.0	ESA
102–103	Erl-13014	V nH-M	Bulk sample	3761 ± 46	2335–2031 BC	−28.0	MSB
114–115	Erl-13015	V nH-M	Bulk sample	4346 ± 48	3091–2891 BC	−28.0	ESB
130–131	Erl-13016	VI nH	Bulk peat sample	6735 ± 54	5729–5559 BC	27.2	EA
144–145	Erl-11887	VI nH	Bulk peat sample	6667 ± 54	5666–5489 BC	−25.8	EA

The dates were calibrated using the calibration dataset of Reimer *et al.* (2004). Calibrated ages are rounded off (by 10) where standard deviation is ≥50 years. The calibrated ^{14}C ages are correlated to the chronozones defined by Mangerud *et al.* (1974). EA, Early Atlantic; MA, Middle Atlantic; ESB, Early Subboreal; MSB, Middle Subboreal; ESA, Early Subatlantic.

determined, which corresponds to the Early Atlantic Period. Two ^{14}C ages from 117–116 cm (5971–5723 a cal. BC, 2σ, Erl-11879) and 113–112 cm (5562–5491 a cal. BC, 2σ, Erl-11878) are dated to the Early Atlantic Period, specifically to the transition from the Early Atlantic to Middle Atlantic Periods. The age determinations from 92–91 cm (2017–1745 a cal. BC, 2σ, Erl-7290) and 75–74 cm (1916–1687 a cal. BC, 2σ, Erl-7289) display overlapping error ranges; however, the ages still correlate to the Middle Subboreal Period. In conclusion, the profile section from 153 to 74 cm represents the cultural periods from the Late Mesolithic Period to the Early Bronze Age.

For profile 7038-306, the ^{14}C ages from the base at 145–144 cm depth (5666–5489 a cal. BC, Erl-11887) and at 131–130 cm (5729–5559 a cal. BC, Erl-13016) show an age inversion. Both age determinations correspond to the Early Atlantic Period. The subsequent three radiocarbon ages are consistent, with age determinations at 115–114 cm (3091–2891 a cal. BC, Erl-13015), at 103–102 cm (2336–2031 a cal. BC, Erl-13014) and at 79–78 cm (94 a cal. BC to 123 a cal. AD, Erl-11886). The ages correspond respectively to the Early Subboreal, Middle Subboreal and Early Subatlantic Periods. Therefore, the profile section from 145 to 78 cm represents the cultural periods from the Late Mesolithic Period to the transition from the La Tène Period (Iron Age) and to the Roman Empire.

Although the ^{14}C ages are generally consistent, the age determinations with overlapping error ranges of profile 7038-302 and the age inversion at the base of profile 7038-306 indicate inconsistencies in the chronology. These problems are most probably associated with the material dated. In profile 7038-302, the ages with the apparent overlapping error ranges from the top were determined from wood. It is possible that the wood is root wood and therefore dates from the same root could be an explanation. Concerning the age inversion at the base of profile 7038-306, bulk samples mainly composed of rootlets (sedge peat) were dated in both cases. Root penetration from above could be the cause of the age inversion and result in the younger ages at the base (e.g. Charman 2002). A further explanation could be contamination by mobile humic acids moving downwards and/or laterally, which might result in ages which are too young. However, with the knowledge of possible contamination by humic acids, the ^{14}C samples were chosen from several centimetres above the peat base. Taking these factors into account, we assume that the ages are most probably too young rather than too old.

In summary, these inconsistencies make it difficult to construct accurate age–depth models, and the calculation of accumulation rates was therefore omitted. Also, the correlation of the radiocarbon ages with distinct cultural settlement periods is problematic because of the wide error ranges of the calibrated 2σ ages. Nevertheless, the ^{14}C ages provide a chronological framework for the reconstruction of environmental history and human impact.

Reconstruction of the fire history in the *Siedlungskammer* Burgweinting in relation to settlement and environmental history

Combining the results from stratigraphic, geochemical, and microscopic charcoal investigations with the chronological information from the two sequences (7038-302 and 7038-306) derived from the Islinger Mühlbach Fen and the available palaeoenvironmental and archaeological information, the following fire history and implications for the environment in the *Siedlungskammer* Burgweinting could be reconstructed (Fig. 9).

Late Mesolithic (c. 8000–5500 a cal. BC)

In Central Europe during the Early Atlantic period the environmental conditions were generally stable (Kalis *et al.* 2003). The vegetation was natural and the landscape was covered with woodland. There are only a few traces of human occupation, although the presence of a Mesolithic population is documented by archaeological finds and by charcoal fragments in lake sediments. However, no major human impact on the environment has been found (Kalis *et al.* 2003).

In the surroundings of the *Siedlungskammer* Burgweinting, during the Late Mesolithic Period (Early Atlantic Period), the Islinger Mühlbach Fen was an already established landscape component. Peat growth continued and the spatial spread of the fen is indicated by the radiocarbon ages from the basal peat at the margin of the fen (profile 7038-306) dating to the Early Atlantic Period. It is assumed that Mesolithic people were present in the Regensburger Altsiedelland.

Taking the problems of the radiocarbon ages discussed above into account, FE 1–4 in profile 7038-302 should correspond to the Late Mesolithic to the Early Neolithic transition. Two phases with lower fire activity (FE 1 and FE 3) and two phases with enhanced fire activity (FE 2 and FE 4) can be distinguished (Fig. 9). The same time interval most probably correlates to FE 1–3 or 1–4 in profile 7038-306. Charcoals were found in the upper part of the loess loam and the loess–peat transition horizon, representing FE 1. This is followed by FE 2 with the highest microscopic charcoal

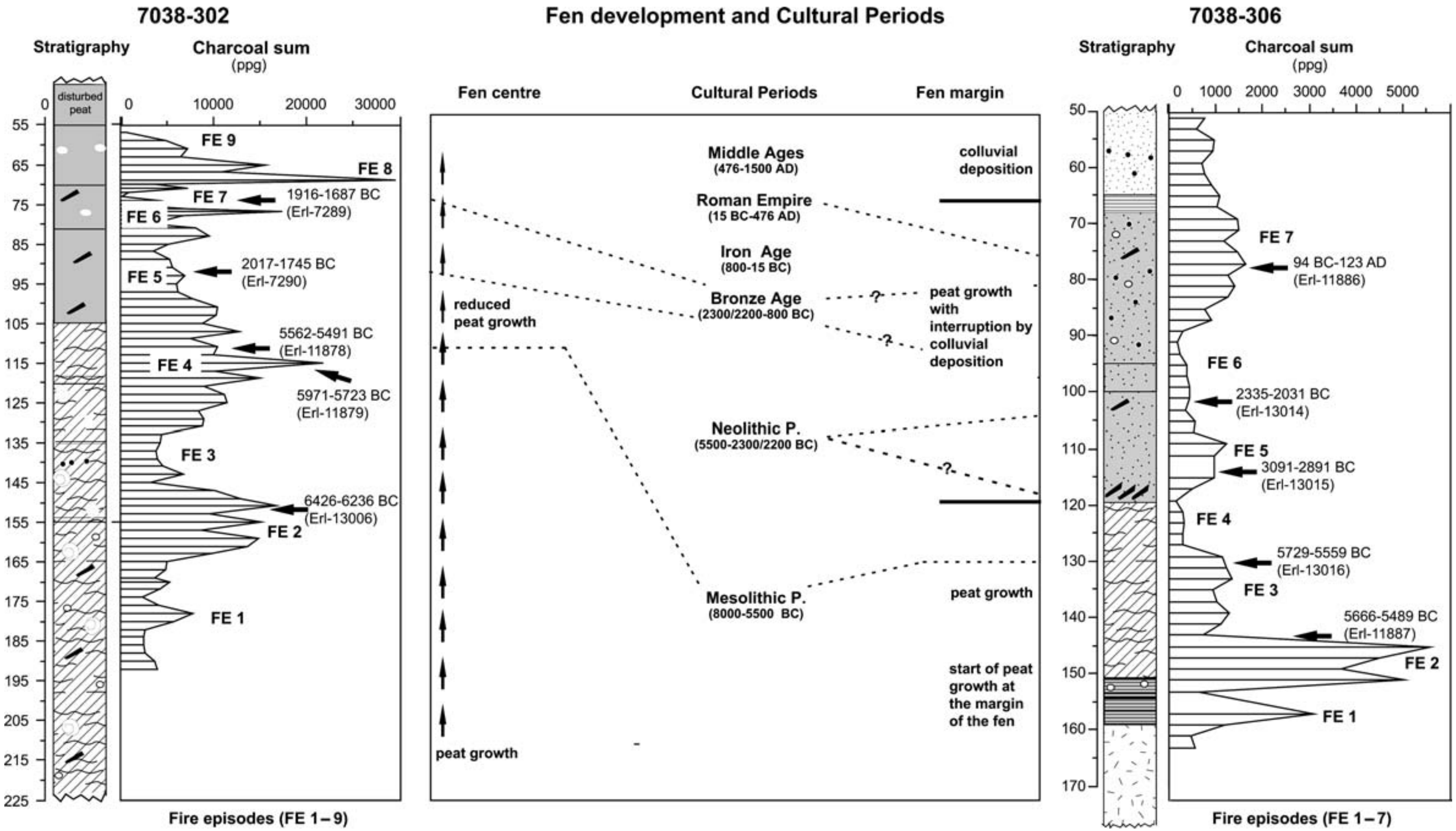


Fig. 9. Reconstructed fire history (charcoal records of profiles 7038-302 and 7038-306) and development of the Islinger Mühlbach Fen correlated with the settlement history in the *Siedlungskammer* Burgweinting.

particle counts throughout the profile. The two ^{14}C ages above FE 2 show an age inversion; however, FE 2 most probably corresponds to the Late Mesolithic Period. Significantly lower microscopic charcoal counts are present in FE 3, which is followed by still lower counts in FE 4. In summary, the depth curve shows the highest fire activity at the base of the sequence followed by decreasing fire activity.

Although the charcoal sum curves of the two profiles show different patterns, the high abundance of charcoal particles in the profile sections correlating to the Late Mesolithic Period to the Neolithic transition document the relevance of fire in the environment. However, the origin of the charcoal particles, natural lightning-induced fire v. deliberate use of fire by people, has been much discussed. Some researchers (e.g. Ellenberg 1996; Kaal *et al.* 2008) have stated that temperate deciduous forests would rarely burn naturally because the woodland composition is not flammable. Thus, charcoal particles incorporated in peat and sediments have been interpreted to indicate human-induced fire. However, in the Regensburg region there is evidence that the woodland included a high proportion of pine. Charcoal analyses of a Linear Bandceramic site (Early Neolithic Period) near Mintraching yielded an unusually high proportion of charcoal derived from coniferous trees, and therefore forests composed of oak and pine are inferred for the Early Neolithic Period (Kreuz 1990). In addition, pollen analyses of a sediment sequence from a palaeo-meander near Sarching and of a peat–colluvium sequence of the Kirchenmoos Fen support this inference (Knipping 2005; Raab *et al.* 2005). It is believed that prior to and during the Early Neolithic Period, a similar woodland composition existed in the study area. Consequently, the possibility of the occurrence of lightning-induced fires cannot be completely excluded, as conifers may catch fire spontaneously (Kalis *et al.* 2003).

The deliberate use of fire by Mesolithic hunter–gatherers is still debated (Kaal *et al.* 2008), although many studies in various European regions have proven the use of fire by Mesolithic people to open the landscape, increase vegetable and animal food resources, and facilitate the mobility of human groups (e.g. Clark *et al.* 1989; Rösch 1996; Moore 2000; Urz 2000; Bos & Urz 2003; Gerlach *et al.* 2006; Andrič 2007; Kaal *et al.* 2008). It has been assumed that fire was used to aid hunting of big game by keeping the landscape free of dense woodland cover (e.g. Bos & Urz 2003).

The charcoal record of the Islinger Mühlbach Fen presumably derives partly from herbaceous plants, suggesting the burning of mire vegetation. Reed-swamp burning by Mesolithic people was suggested by Bos *et al.* (2005) for the Mesolithic sites near Zutphen (The Netherlands) and by Dark (1998) for the site at Star Carr (North Yorkshire, UK). Also, Innes & Simmons (2000) concluded that substantial fires occurred on and at the edge of peat mires during the Early Mesolithic to Iron Age at North Gill (North York Moors, UK). The use of fire by Mesolithic hunter–gatherers in the *Siedlungskammer* Burgweinting should therefore be considered. Additional evidence that supports our assumption and proves the anthropogenic impact on the landscape during the Mesolithic Period in the Regensburg region is colluvium deposits containing charcoal-rich layers, which are present in the valley of the Kleine Laaber *c.* 20 km SE of Regensburg (Niller 2001).

Neolithic Period (5500–2300 or 2200 a cal. BC)

The Neolithic Period (5500–2300 or 2200 a cal. BC) is correlated to the Atlantic chronozone, the time interval between 8000 and 5000 a BP, also known as the Holocene climatic optimum or Mid-Holocene Hypsithermal (Meyers & Lallier-Vergés 1999; Kalis *et al.* 2003). According to Pott (1992), the vegetation of oak–mixed Atlantic forests was mainly composed of *Quercus*, *Ulmus*, *Tilia*, *Fraxinus* and *Alnus*, but their proportions varied in space and time. In the loess areas south of Regensburg, deciduous forests also existed (Bakels 1992). Pollen analyses from the Kirchenmoos Fen showed that during the Late Neolithic Period, a more or less closed primeval deciduous forest existed, including oak, elm, lime, maple and beech (Raab *et al.* 2005). Pine was an important woodland component (Kreuz 1990; Knipping 2005; Raab *et al.* 2005).

There is abundant archaeological evidence for Neolithic population in the Regensburger Altsiedlland. Several findings of ceramic shards north of the excavation site in Burgweinting document the presence of Neolithic people in this *Siedlungskammer*. The settlements were present on the lower terrace of the Danube; for example, the Linear Bandceramic site at Mintraching (Kreuz 1990). This indicates a lower groundwater level for this time period.

The introduction of the Neolithic subsistence system involved the establishment of permanent settlements and the introduction of agriculture and animal husbandry, and therefore comprises a variety of related activities that would have an impact on the environment in the settlement surroundings. Nevertheless, it is assumed that the human impact on the woodland was comparatively low. Lüning & Kalis (1992) concluded that only small and disjointed areas around the settlements were cleared of forests. Behre (2000) assumed that open grazed forests existed around the settlements. It is estimated that 5–6% of the woodland in South and West Germany was thinned out (Lüning & Kalis 1992). According to Bakels (1992) the people of the Linear Bandceramic culture, settling on the loess soils in the Netherlands, Belgium and Northern France, did not open large areas of the forests, but as a result of their impact the woodland composition changed. In the Kirchenmoos sequence, a colluvium deposited on the mire during the Neolithic Period suggests intensified human activity (Raab *et al.* 2005).

In profile 7038-302 from the centre of the Islinger Mühlbach Fen, the section from *c.* 111 to 92 cm depth correlates to the Neolithic Period based on radiocarbon dating. Peat formation continued, although the degree of humification increases from highly humified peat to amorphous peat. Furthermore, radiocarbon dating of this section indicates a decline in peat growth (Fig. 9). It is assumed that a change in the hydrological balance (e.g. a lowered local water table resulting in increased aeration of the upper peat layer) could be responsible. The reason for the enhanced decomposition, whether caused by natural climatic conditions or by human impact, is debatable.

In the charcoal record of profile 7038-302, the Neolithic Period is represented between FE 4 and FE 5 (Fig. 9), with comparatively high but decreasing charcoal abundance towards lower profile depth. In profile 7038-306, the Neolithic Period is included in the section from *c.* 130 to *c.* 105 cm. In this section, a stratigraphic change from peat to organic-rich colluvium is present at 117 cm, indicating that peat formation was interrupted by colluvial deposition. Colluvium formation is a direct evidence for deforestation and agricultural use of the adjacent slopes to the south. In the same profile section, an abrupt rise in total nitrogen content is detected (Fig. 6). This could indicate nitrification by human activity at the margin of the fen, adjacent to an agricultural field or a track along the fen. A high degree of nitrification caused by local human presence was also found by Urz (2000) and interpreted from macrofossil analyses.

The Neolithic Period most probably corresponds to FE 4 and 5. Whereas during FE 4 (peat), the microscopic charcoal counts are comparatively low, the abundance of charcoal particles increases in FE 5 (organic-rich colluvium).

During the Neolithic Period several sources for microscopic charcoal production have to be considered, such as woodland clearance for agricultural use or domestic fireplaces. Concerning charcoal transport, other than aerial transport and deposition, at the margin of the fen, water transport by surface runoff is possible, as well as incorporation into colluvial material and subsequent deposition. Near-surface transport can also account for the disintegration of the charcoal particles (Umbanhowar & McGrafth 1988; Clark *et al.* 1998).

In summary, the Neolithic Period is reflected in profile 7038-302 by a decreasing charcoal abundance. This is in accordance with the results of the charcoal record from profile 7038-306. However, comparing the charcoal peak curves, it becomes obvious that pre-Neolithic burning was more important than later biomass burning. This could be connected with the availability of combustible material in the vicinity of the fen. It is also possible that slash-and-burn practices became less important because they were no longer needed, and instead fire was used only to keep the agricultural fields open.

Bronze Age (2300 or 2200–800 a cal. BC)

At the beginning of the Bronze Age at 3500 a BP, stable oceanic climatic conditions existed. In general, according to Magny (1982), drier phases persisted during the Early Bronze Age (2200–1800 a cal. BC) and during the Urnfield Period (1200–800 a cal. BC), and between these periods, the climate was slightly wetter. The relatively dry climatic conditions during the Urnfield Period are inferred from lower lake levels throughout Europe.

In the *Siedlungskamme*r Burgweinting, the absence of finds for the cultural periods from the End-Neolithic (*c.* 2200 a BC) to the Urnfield Period (*c.* 1200 a cal. BC) (Zuber 2006) suggests a hiatus in settlement activities (*Siedlungsruhe*) lasting for about 1000 years. Likewise, in the Federsee region (West Germany), the Early Bronze age is not documented by archaeological finds, and therefore a period of *Siedlungsruhe* is inferred (Maier & Vogt 2007). In contrast, pedological and mire investigations by Maier & Vogt (2007) proved that the Early Bronze age period is reflected by particularly high sedimentation rates and a striking abundance of charcoal fragments. We therefore suggest that further archaeological research in this area is required.

At the beginning of the Urnfield Period, a noticeable rise in population is recorded in the *Siedlungskammer* Burgweinting and in the surroundings of Regensburg. So-called Urnfield hilltop settlements were established; for example, at the Weltenburger Frauenberg, the Bogenberg near Straubing, and the Schloßberg above Kallmünz (Schauer 1998; Rind 1999; Neudert 2003; Sandner 2005).

The sediment sequence from the palaeomeander of the river Danube near Sarching shows intensified soil erosion and deposition of alluvial clay, proving an increased human impact (Knipping 2005). This is also reflected in the pollen diagram with an alteration of the woodland composition; however, pine remains an important forest constituent (Knipping 2005). In the Kirchenmoos area, the forest-free areas most probably did not greatly increase, and the woodland composition remained similar to that during the Neolithic Period with the addition of hornbeam (Raab *et al.* 2005).

For the first time, the pollen diagram from the sequence near Sarching shows a closed curve of cereal-type pollen, suggesting a continuous agricultural practice (Knipping 2005); also, cereal cultivation is documented in the Kirchenmoos area (Raab *et al.* 2005). According to Küster (1995), during the Early Bronze Age (Chamer Gruppe) a clear change in the economic basis of agriculture took place, with a decreasing importance of wheat (*T. monocuccum*) and increasing importance of spelt (*T. spelta*) and barley (*Hordeum vulgare*). Furthermore, wheats (*T. aestivum*, *T. monocuccum* and *T. dicoccum*) and millets (*Panicum miliaceum* and *Setaria italica*) were cultivated. From that point forward, no substantial change in cultivated plants occurred in Bavaria until the Middle Ages (Küster 1995).

In the peat profile 7038-302, the section between 92 and 74 cm probably corresponds to the Bronze Age. The overlapping error ranges of the radiocarbon ages exclude a correlation with distinct settlement periods. Based on the charcoal record, FE 5–8 represent the Bronze Age. Following the charcoal peak at the Mesolithic–Neolithic transition, a decrease in charcoal abundance is visible towards FE 5. The samples between 82 and 69 cm depth were continuously analysed to gain more detailed information. A short-term increase in charcoal abundance is visible in FE 6. Subsequently, during FE 7 the lowest charcoal abundance throughout the profile is detected, which is followed by the highest charcoal abundance (FE 8) throughout the profile. It is assumed that FE 7 might correspond to the Early to Middle Bronze Age settlement gap with a lack of finds in the archaeological excavation, even though this 5 cm thick section might represent less than 1000 years. FE 8 could then represent the Urnfield period (1200–800 a cal. BC) with very high charcoal abundance. In profile 7038-306, the radiocarbon age from 102 to 103 cm depth shows that this profile section belongs to the Bronze Age. Organic-rich colluvia are present, which cannot be better defined because of the compaction problem associated with the coring technique, but the mineral substrate proves soil erosion. This section corresponds to FE 6 with comparatively low charcoal abundance, which could also reflect the Early to Middle Bronze Age break in settlement activity. The following Urnfield Period could be represented by the increasing charcoal abundance towards FE 7 in the core.

The charcoal peak in the record does not seem adequate to reflect the intensive use of the *Siedlungskammer* Burgweinting during the Urnfield Period, documented in the archaeological excavations (Zuber 2004*b*, 2006). An explanation might be that the landscape was already opened and forest clearance by fire was no longer practised. Furthermore, there must have been a high need for firewood, and wood for construction and other settlement activities and use in burial customs.

Bronze Age (2300 or 2200–800 a cal. BC) to Iron Age transition, Iron Age (800–15 a cal. BC) and Roman Empire (15 BC–AD 476)

According to Dark (2006) a major climate downturn occurred at 850 a cal. BC, at the Bronze Age to Iron Age transition, causing settlement abandonment in western Europe. A global cooling around 2800 a cal. BP (850 a cal. BC) has also been described by Denton & Karlèn (1973), Bond *et al.* (1997, 2001) and van Geel *et al.* (1999).

According to the pollen diagram from Sarching (Knipping 2005), an intensified anthropogenic impact on the vegetation is noticeable, with a decrease in the arboreal pollen percentages indicating that the woodland is strongly reduced. Pine remains the dominant woodland constituent, but the QM (Quercetum Mixtum) species (*Quercus*, *Ulmus*, *Tilia*, *Acer*, *Fraxinus*) and *Fagus* as well as *Salix* percentages decrease. The presence of *Plantago lanceolata* pollen documents pastures and increased cereal pollen percentages indicate increased agricultural use. No further information is available from this profile, because the pollen analytical processing of younger sediments is not possible.

The results of the archaeological excavation in the *Siedlungskammer* Burgweinting indicate a significant local population decline following the Urnfield Period. According to Brunnacker (1994), during Celtic times prior to the Roman invasion, agriculture was comparatively highly developed, as indicated by soil erosion. Intensive soil erosion induced by agricultural use is documented by studies at the Celtic square enclosure (Viereckschanze) Poign (Leopold 2003; Leopold & Völkel 2007).

The charcoal record of profile 7038-302 shows a decreasing charcoal abundance following the Bronze Age until the end of the analysed profile at 55 cm depth (FE 9). In contrast, profile 7038-306 shows an increase in charcoal abundance towards 78–79 cm depth, which is dated to 94 a cal. BC–AD 123 a cal. (Erl-11886, 2σ) corresponding to the transition from the La Tène Age to Roman Empire.

In profile 7038-306 the La Tène Age to Roman Empire transition corresponds to the peat–colluvia complex, documenting soil erosion induced by agricultural use. The charcoal record shows a steady increase of charcoal abundance (FE 7), which remains high with a slight bias to decreasing abundance towards the top.

Based on archaeological research, no immediate succession from the La Tène Age to the Roman Empire has been detected in the Burgweinting excavation or in the Regensburg region. This is in contrast to the charcoal record of profile 7038-306, which shows that charcoal is continuously present during the corresponding time interval, with increasing charcoal abundance towards the Roman Empire times.

The settlement conditions during the time of the Roman Empire were certainly supported by the favourable climatic conditions. Based on archaeological finds, the settlement by a Roman rural population in the *Siedlungskammer* Burgweinting starts contemporaneously with the establishment of the legionary fort at Kumpfmühl (*c*. AD 79). Four *villae rusticae* present in an area of 25 ha document an intensive use of the *Siedlungskammer* Burgweinting. Assuming an estimated agricultural land of 50–120 ha per *villa rustica*, the woodland must have been strongly reduced during the Roman Empire because of the enormous need for wood for domestic use and constructions by the rural population, as well as the civil urban population and the military base.

Information from the charcoal records for Roman Empire times is available only from profile 7038-306 corresponding to FE 7, with a high charcoal abundance in the peat–colluvia substrate, which documents agricultural use of the adjacent field south of the fen. The top of the profile is formed by colluvium with low organic content, indicating that peat formation at the margin of the fen was completely stopped by colluvium deposition continuing most probably to the Middle Ages.

Conclusions

(1) Charcoal fragments that are present in the investigated profiles of the Islinger Mühlbach Fen indicate the occurrence of fire in the environment. Although the possibility that the charcoal particles derive from wildfires cannot be completely ruled out, the charcoal records are interpreted to be most probably produced by primarily anthropogenically induced fires, as the presence of humans in the study area for thousands of years is documented by archaeological evidence.

(2) The two profiles investigated, one from the centre of the fen and one from the margin, represent different sinks for palaeoenvironmental data. However, the records provide overlapping and complementary information about environmental history and human impact, using the profile stratigraphy, geochemical analyses and microscopic charcoal analyses as a fire proxy.

(3) The chronological control of the cores is problematic, but the ages determined, in combination with the charcoal records, suggest the deliberate use of fire since Mesolithic times. Mesolithic hunter–gatherers could have practised reed-swamp burning to open the vegetation for hunting. For further evidence, the determination of the charcoal species would be helpful. Based on the high abundance of charcoal particles in the profile sections correlating to the Mesolithic Period, fire played a prominent role in the environment. The Mesolithic population is barely documented by archaeological evidence or by palaeoecological data such as pollen records, but is indicated by the charcoal records. The deliberate use of fire by the Mesolithic hunter–gatherers would furthermore imply that the Neolithic farmers did not enter a primeval environment.

(4) The continuous occurrence of charcoal particles in changing quantities indicates continuous settlement activities. The fire episodes distinguished extend over several centimetres or decimetres of the records, which represent hundreds to thousands of years. Because of the wide error ranges of the radiocarbon ages, the fire episodes cannot be correlated to distinct settlement periods.

(5) In the charcoal record, there is a single section with low charcoal abundance, which might reflect a general decline in the intensity of human activity in the catchment. The absence of finds for the settlement periods from the End-Neolithic to Urnfield Period, which is interpreted as a *Siedlungsruhe*, could correspond to this decline in charcoal abundance. According to the archaeological information, this time interval extends over *c*. 1000 years. In contrast, in the record this period is represented by a peat section that is only 5 cm thick, suggesting either that the duration of this *Siedlungsruhe* might be shorter than 1000 years or that peat accumulation was very low during this time interval.

(6) The prominent role of the Urnfield period in the settlement history of the *Siedlungskammer* Burgweinting, lasting for about 300 years, is not as markedly represented in the charcoal records as one might assume. A possible explanation could be that the woods were already opened and forest clearance by fire for arable land was not necessary. Sources for charcoal production are domestic use, processing of bronze and cultural activities. Most probably because of the high population density, there was great a demand for firewood, wood for construction, tools and other related settlement activities.

(7) Further information about the human–landscape interrelationship, and especially the

relationship between fire and vegetation, is expected from pollen analyses, which are in progress.

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