

Peat accumulation in kettle holes: bottom up or top down?

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SUMMARY

Rapid peat formation in kettle hole-shaped basins may take place either a) by peat forming downwards (top down) from a floating mat under stable water level conditions (terrestrialisation), or b) by peat forming upwards (bottom up) as humus colloids seal off the basin, causing the water level to rise progressively (“kettle hole mire mechanism”). The latter mechanism has hardly been considered in the international literature. The floating-mat mechanism must lead to concave peat isochrones throughout the basin, whereas the kettle hole mire mechanism will yield surface-parallel isochrones. Peat isochrones were studied in three mires occupying kettle hole-shaped basins in north-eastern Germany by comparing pollen samples from the mineral soil–peat interface at different distances from the centre of each mire with the pollen assemblage profile of a central peat core. All three mires appeared to have largely surface-parallel isochrones and must have developed by the kettle hole mire mechanism. In one mire, this mechanism alternated and took place in combination with terrestrialisation following karst subsidence. The fact that evidence of the kettle hole mire mechanism was found at all of the sites investigated indicates that it may be a common peat forming mechanism in kettle hole-shaped basins worldwide.

KEY WORDS: kettle hole mire, mire development, peat accumulation, peat isochrones, pollen analysis.

INTRODUCTION

Kettle hole-shaped basins that have developed by thawing of residual ice after deglaciation or as a result of karst (Succow 1988, Timmermann & Succow 2001) are common landscape features throughout the boreal and temperate zones (Timmermann 2000). They are abundant in moraine areas and, after various initial lake and mire stages, often support oligotrophic-acid peatland vegetation typical of ombrotrophic conditions, even in rather dry climates (Timmermann 1999, Booth *et al.* 2004). The kettle hole shape with its steep slopes promotes such oligotrophic vegetation and the associated formation of *Sphagnum* peat in the centre of the mire by supplying rather nutrient-poor interflow water from the surrounding catchment, and by reducing evaporation losses through shading and limiting air exchange (Edom 2001, *cf.* Warner 1993). Mires in kettle hole-shaped basins show peat accumulation rates which – at up to 5 mm yr⁻¹ – are amongst the highest in existence (Wilcox & Simonin 1988, Couwenberg *et al.* 2001).

The high accumulation rates of these mires and the fact that the mire water level in the basin is often independent of – and distinctly higher than – the regional groundwater led Klafs *et al.* (1973) to postulate a special hydrogenetic mire type, the “kettle hole mire” (*cf.* Joosten & Clarke 2002). This

mire type is thought to exhibit a mechanism of “self-sealing”, by which precipitation of humus colloids from the peat seals off the mineral soil at the interface of mire and basin. This raises the drainage level and thus the water level in the basin, so that peat growth and humus precipitation occur at progressively higher levels (Timmermann 1999, Joosten & Succow 2001, Timmermann & Succow 2001).

Although the peat stratigraphy and the hydrological conditions of many mires in kettle hole-shaped basins make the existence of such a self-sealing mechanism plausible (*cf.* Hemond 1980, Timmermann 1999), no proof has been available that these mires really do grow upwards as a result of rising water levels. Furthermore, the mechanism has received little attention in the international literature because another common peat formation mechanism, namely floating mat terrestrialisation, could equally explain the gross stratigraphy and the rapid accumulation rates (*cf.* Joosten 1995). Which of these mechanisms applies can be tested by studying peat isochrones, which are lines connecting peat layers of the same age (*cf.* Punning *et al.* 1995).

In the case of floating mat terrestrialisation, peat is formed beneath the vegetation mat and gradually sinks into the water body under the weight of peat that subsequently forms above it, until the basin is filled completely (= “top down”). In a situation

where the water level is stable, this “top down” (sedimentary) peat accumulation results in concave isochrones that follow the shape of the basin. Samples from the mineral soil–peat interface would be of the same age throughout the basin. Moreover, a floating or submerged vegetation mat that did not cover the entire basin (*cf.* Swan & Gill 1970) would – in the cases of both centrifugal and centripetal encroachment – lead to the deposition of organic detritus sediments of the same age across the whole floor of the basin (*cf.* Davis *et al.* 1984, Kratz & DeWitt 1986). All samples of bottom peat would be

of the same age, and older than samples from a central core (Figure 1).

The self-sealing mechanism, on the other hand, should result in straight isochrones because the peat grows “bottom up”, parallel to the rising water surface. Samples from the mineral soil–peat interface would be oldest at the centre of the basin and become younger towards its edges (Figure 1).

This paper aims to elucidate the peat formation mechanisms at three mires in kettle hole-shaped basins in north-eastern Germany by reconstructing their peat isochrones.

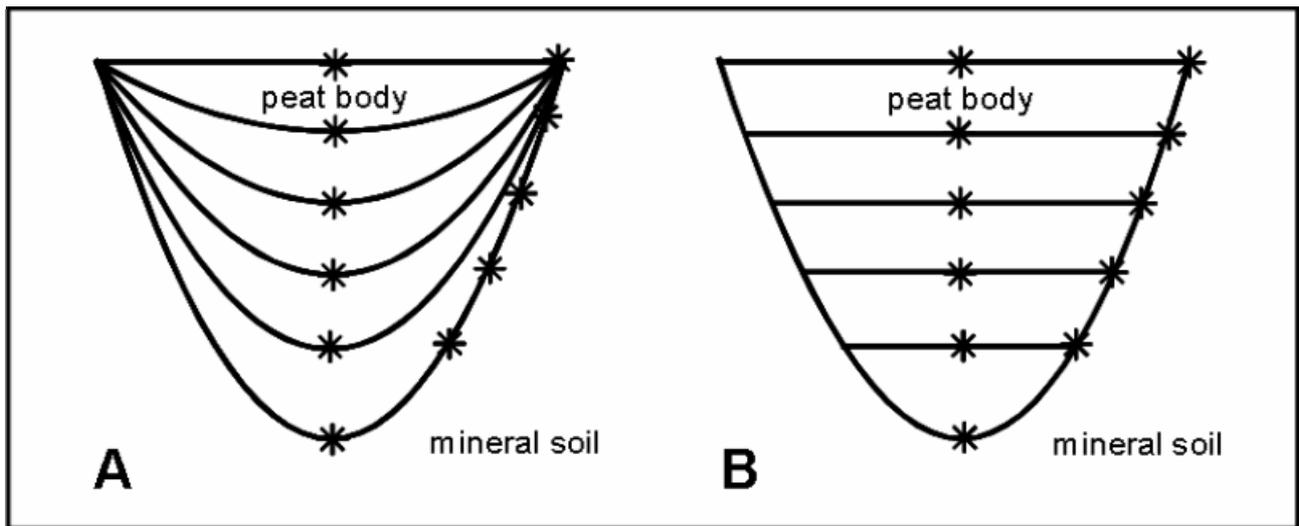


Figure 1. Hypothetical peat isochrones resulting from (A) floating mat terrestrialisation and (B) self-sealing mire formation. Sample locations are indicated by *.

METHODS

Study sites

Three mires in kettle hole-shaped basins were selected (Figure 2) on the basis of their high peat accumulation rates (*cf.* Couwenberg *et al.* 2001). The surfaces of all three mires are flat, and they are situated in moraine hills covered by *Fagus sylvatica* and *Fagus sylvatica-Quercus robur* forests. The climate is temperate with mean annual temperature *ca.* 8°C and mean annual rainfall 600 mm (Grosse Wiese), 800 mm (Herthamoore) and 530 mm (Kreuzfenn) (DWD 2006, NLP Jasmund 2006).

The “Grosse Wiese” (3.2 ha, 54° 23’ N, 13° 39’ E, 18 m a.s.l.) is located 300 m from the coast of the island of Rügen in the Baltic Sea (north-east Germany). Its vegetation consists of open stands of small *Betula pubescens* and *Pinus sylvestris* trees, *Ledum palustre*, *Oxycoccus palustris*, *Eriophorum vaginatum* and various *Sphagnum* species (*S. recurvum* group, *S. magellanicum* and *S. rubellum*).

The “Herthamoore” (1.4 ha, 54° 34’ N, 13° 38’ E, 114 m a.s.l.) is also located on Rügen. Its vegetation consists of *Molinia caerulea*, *Eriophorum angustifolium*, *E. vaginatum*, *Sphagnum fallax*, *Deschampsia flexuosa*, *Pteridium aquilinum* and *Betula pubescens* (Paulson 2001).

The vegetation of the “Kreuzfenn” (3.6 ha, 52° 53’ N, 14° 00’ E, 95 m a.s.l.) consists of rather dense *Pinus sylvestris* (*ca.* 5 m high), *Betula pubescens*, *Ledum palustre*, *Eriophorum vaginatum* and various *Sphagnum* species, with a belt of *Salix aurita* at the transition from peat to mineral soil. The centre of the mire is characterised by the presence of extremely oligotrophent species such as *Sphagnum fuscum* and *Oxycoccus microcarpus*.

Pollen analysis

Peat cores were collected with a chamber peat corer (4.5 cm diameter). Volumetric samples of 0.25 or 0.5 cm³ were taken from the mineral soil–peat interface along a transect from the margin to the



Figure 2. a) Location of the study area in Europe and b) locations of the study sites within the study area.

centre of each mire, as well as from a complete central core (*cf.* Figure 1). Processing involved boiling in 10% KOH, sieving (mesh 120 μm), treatment with HF to remove silicates, acetolysis for seven minutes and mounting in silicone oil (2000 centistokes) (*cf.* Faegri & Iversen 1989). The samples were analysed palynologically using a Zeiss Axiolab light microscope with 400x magnification; pollen and spore nomenclature follows Moore *et al.* (1991). Pollen types are written in SMALL CAPITALS in this text in order to distinguish them from taxa (Joosten & De Klerk 2002).

Complete slides were counted until a basic pollen sum of at least 200 grains was reached. The basic pollen sum includes all pollen ascribed to tree taxa and to upland herbs and cultivated plants, and excludes pollen and spores that might originate from wetland herbs and mosses. PINUS, BETULA and SALIX are excluded from the pollen sums for Kreuzfenn and Grosse Wiese, and for the latter site TILIA is also excluded.

Assignment

Stratigraphically-constrained cluster analysis (Tilia Software Package Version 1.12, Grimm 1992) was used to define Site Pollen Assemblage Zones (SPAZs, each with a characteristic and uniform upland pollen composition *cf.* Birks & Birks 1980) for the three central cores. Age assessments for two of the sites were made by comparing their pollen diagrams with ^{14}C dated diagrams from nearby locations (for Grosse Wiese: Lange *et al.* 1986, Latałowa 1992, Strahl 1997, Schumacher & Bayerl 1997; for Kreuzfenn: Endtmann 1998, Jahns 2000, Müller 1967). Fifteen ^{14}C dates were available for the relevant part of the Herthamoor profile (Endtmann 2002).

Depth-constrained cluster analysis was also used to assess the similarity between adjacent bottom samples (samples from the mineral soil–peat interface). The upland pollen composition of each bottom sample cluster was compared with the upland pollen composition of the appropriate central

core and, if sufficient similarity was apparent, assigned to a specific SPAZ.

As the centre of the mire is – and has (almost) always been – rather distant from the upland, its pollen assemblage will generally reflect the regional deposition of upland pollen types. Bottom samples may, however, acquire strong local and extra-local pollen signals where upland plants have been growing on sloping mineral soil (as occurs in kettle hole basins) close to or, in the case of trees, even over the sampling spot (*cf.* Janssen 1973). An (extra-)local pollen signal may distort the quantitative composition of the bottom-sample upland pollen assemblage to such an extent that no similar assemblage is encountered in the diagram for the centre of the mire (*cf.* Janssen 1973, De Klerk *et al.* 1997). Where (extra-)local occurrence of a taxon was suspected, the hypothesis was tested by removing the “over-represented” pollen type from the pollen sums for both the bottom sample and the central core (*cf.* Janssen 1959) and repeating the attempt to quantitatively match their upland pollen assemblages.

RESULTS

Grosse Wiese

The pollen diagram for the mire centre (GWL, Figure 3) is subdivided into ten pollen assemblage zones, GWL-A to GWL-J. The pollen values for the bottom samples (GWU samples, Figure 4) show clear differences and can be clustered into four distinct groups, GWU-1 to GWU-4.

Cluster GWU-1 (GWU493 to GWU235) is characterised by low FAGUS (<1%) and CARPINUS TYPE (<0.5%) values. This limits correlation to SPAZs GWL-B, GWL-D, GWL-F and GWL-H of the central core GWL, which all have very similar pollen assemblages. A more precise assignment is possible for only two of the samples. The values for ALNUS in all of the GWU-1 samples are higher than in any of these 4 SPAZs. Assuming extra-local over-representation and removing ALNUS from the pollen sum of both GWU and GWE suggests that QUERCUS also shows extra-local over-representation in most samples so that a more detailed correlation to GWL SPAZs is not possible. For samples GWU259 and GWU235, the removal of ALNUS (51%) leads to CORYLUS values of 51% and 57%, and QUERCUS values of 34% and 29% respectively, allowing assignment to GWL-Hd.

Cluster GWU-2 (GWU198 and GWU169) has substantial values of FAGUS (17% and 29%), allowing consideration of four SPAZs: GWL-C, GWL-E, GWL-G, and GWL-I. The high upland-

herbs values (2% and 4%) preclude assignment to GWL-C or GWL-G. The other pollen types do not allow unequivocal assignment to either GWL-E or GWL-I. The occurrence of PICEA pollen makes GWL-I more plausible, however.

Cluster GWU-3 (GWU129, GWU91 and GWU73) can convincingly be correlated with SPAZ GWL-J on the basis of the combination of high FAGUS values (74%, 65%, 73%) and very low TILIA values (0.5%, 0.5%, 0%).

Cluster GWU-4 consists of only one sample (GWU9), which differs from the preceding three clusters because of its high PICEA (8%) and low ALNUS (5%) values. The value for upland herbs is higher (5%), and more cereal pollen (CEREALIA SINE SECALE and SECALE) is found. Such a pollen assemblage is not present in the GWL central core, of which the uppermost 55 cm could not be sampled. The high FAGUS and PICEA values indicate that the sample is probably younger than GWL-J. The PICEA pollen may originate from what is now a 75-year-old *Picea* stand close to the sample site.

Kreuzfenn

The pollen diagram for the centre of the mire (KFG, Figure 5) is subdivided into nine pollen assemblage zones (KFG-A to KFG-I). The pollen values for the bottom samples (KFU samples, Figure 6) show clear differences and can be clustered into four distinct groups, KFG-1 to KFG-4. Basal peat could not be obtained from the very wet margin of the mire (6 m wide, depth <127 cm).

Cluster KFU-1 consists of only one sample (KFU551). The values for CARPINUS TYPE (4%), ALNUS (31%) and QUERCUS (45%) confine possible correlations to SPAZs KFG-B and KFG-E. The FAGUS value of 6% points to SPAZ KFG-E, but this is inconclusive because the value hardly exceeds the maximum value in KFG-B. The CORYLUS value (8%) enables a convincing assignment to KFG-B.

Cluster KFU-2 (samples KFU491 and KFU459) might be assigned to either KFG-D or KFG-E because of the relatively high FAGUS (19%, 11%) and ALNUS (25%, 24%) values. The high QUERCUS value for KFU459 (52%) is consistent with KFG-E, but the FAGUS value for KFU491 points to SPAZ KFG-D, and this assignment is supported by the CARPINUS TYPE values of both samples.

Cluster KFU-3 (KFU404 to KFU289) is assigned to SPAZ KFG-E on the basis of QUERCUS values of 53–66% combined with ALNUS values of 19–30% and FAGUS values of 5–8%. The combination of FAGUS (6%) and QUERCUS (66%) values of KFU404 is found only in SPAZ KFG-F, but the ALNUS value of 19% is found only in KFG-E. The QUERCUS value is only slightly higher than

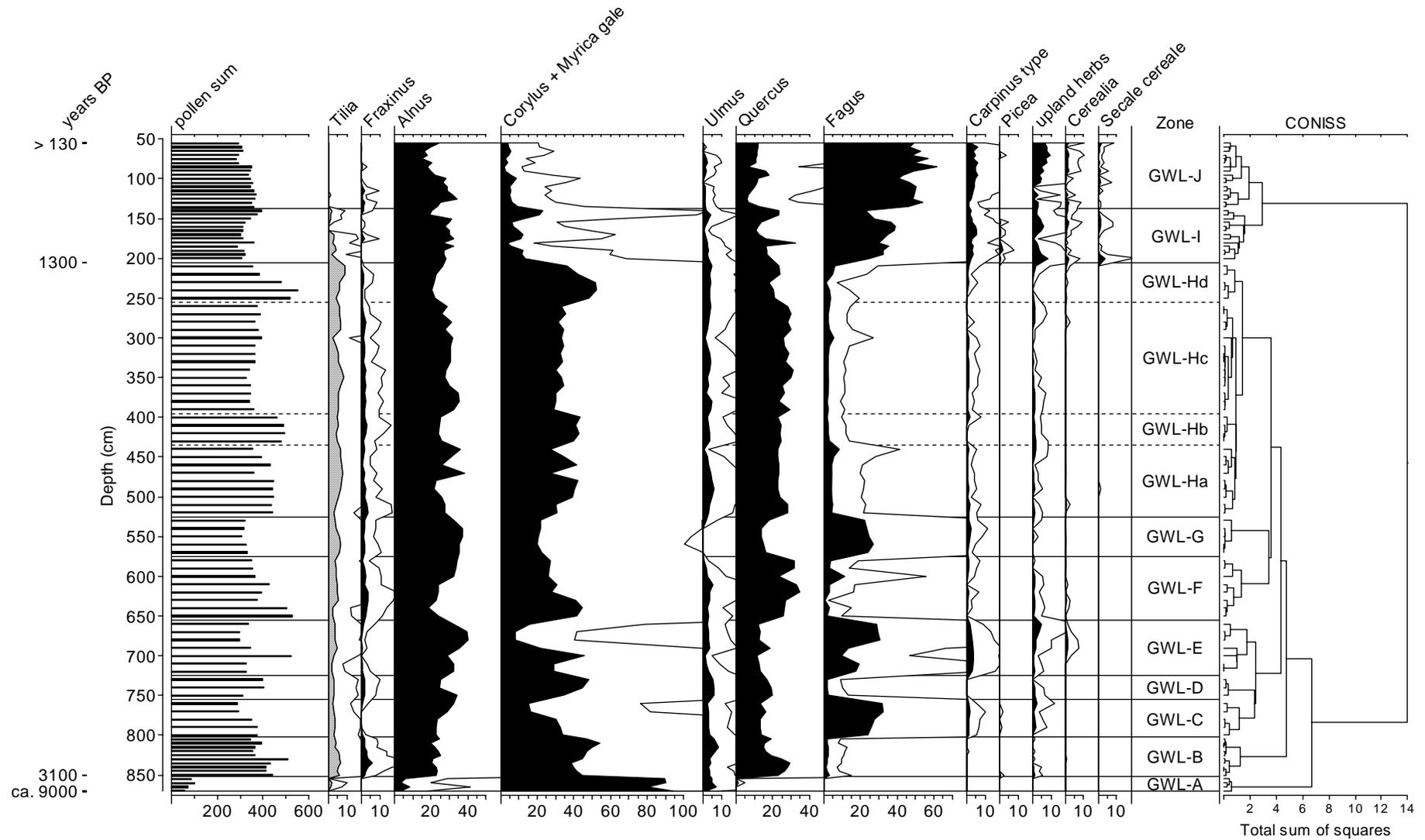


Figure 3. Upland pollen percentage diagram for the centre (GWL) of the Grosse Wiese mire, selected curves only; unshaded curves with 5x exaggeration. SALIX, PINUS, BETULA and TILIA are excluded from the pollen sums (curves hatched or not shown). Sample depths are shown in cm below the water table (\approx the mire surface). Analysis by E. Lange, 1975 (Lange *et al.* 1986).

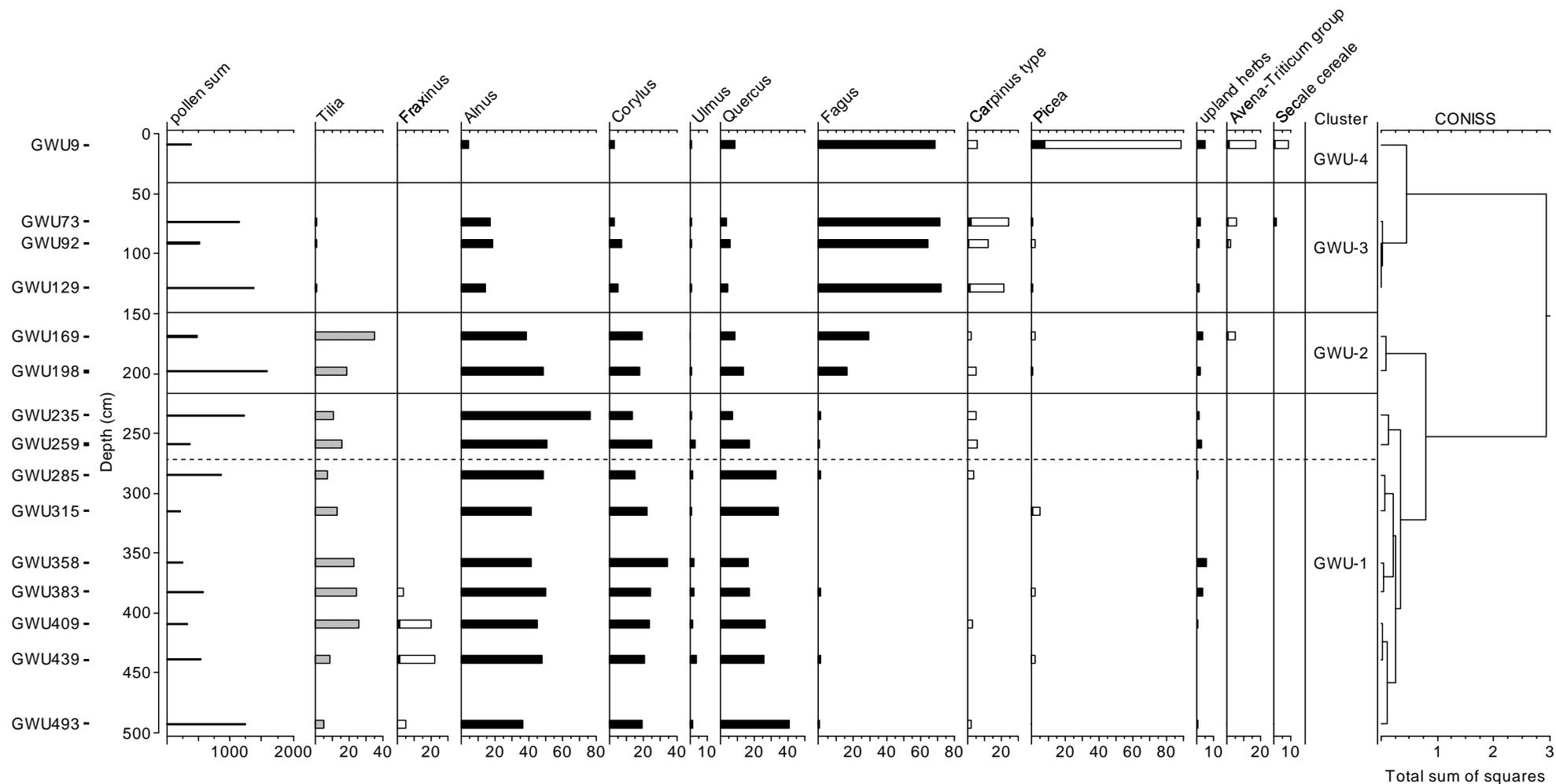


Figure 4. Upland pollen percentage diagrams for samples from the mineral soil–peat interface (GWU) at the Grosse Wiese mire, selected curves only; unshaded bars with 5x exaggeration. SALIX, PINUS, BETULA, and TILIA are excluded from the pollen sums (bars hatched or not shown). Sample depths are shown in cm below the water table (\approx the mire surface). Analysis by G. Gaudig, 2000.

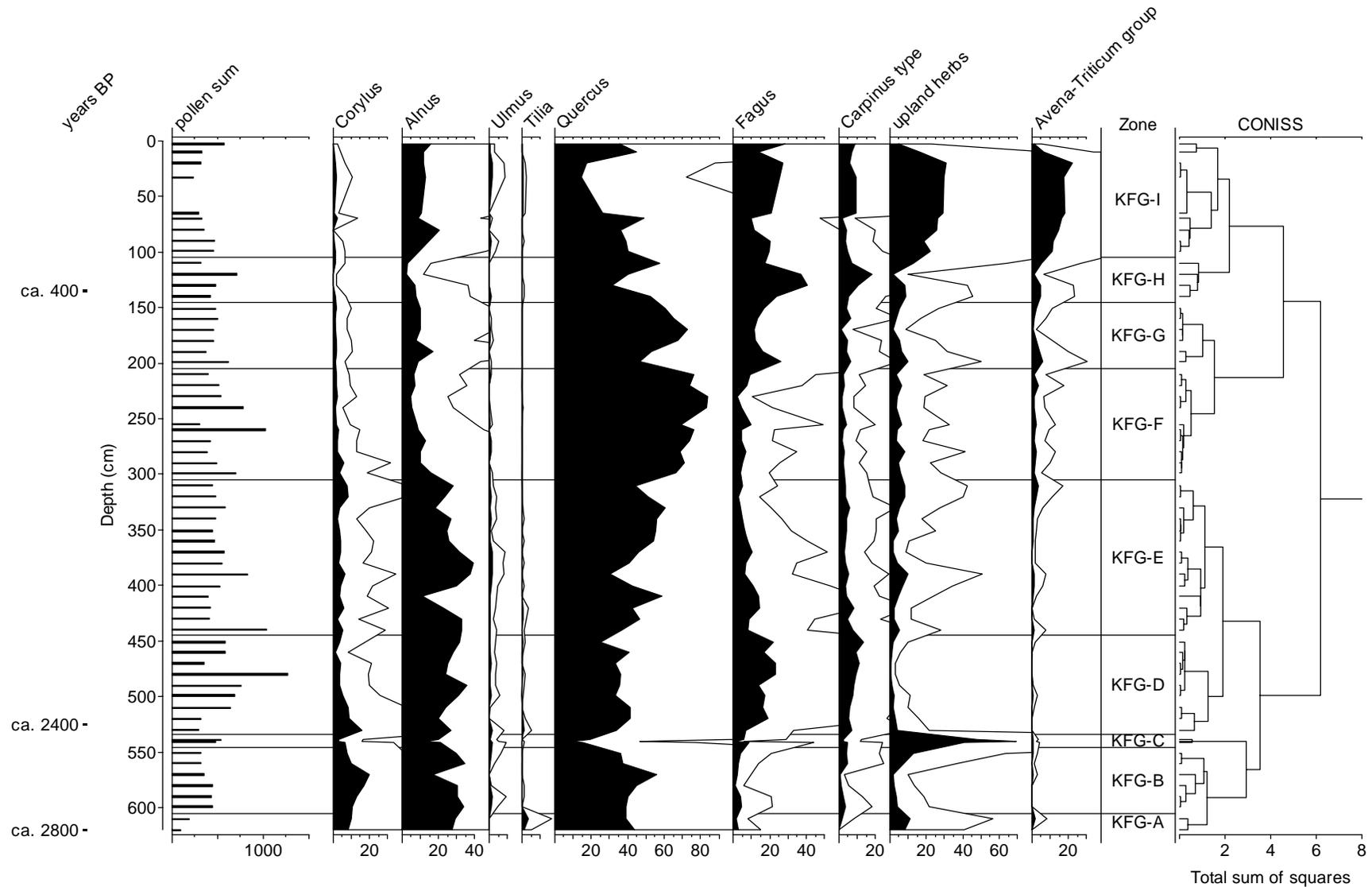


Figure 5. Upland pollen percentage diagram for the centre (KFG) of the Kreuzfenn mire, selected curves only; unshaded curves with 5x exaggeration. SALIX, PINUS and BETULA are excluded from the pollen sums (curves not shown). Sample depths are shown in cm below the water table (\approx the mire surface). Analysis by G. Gaudig, 2000.

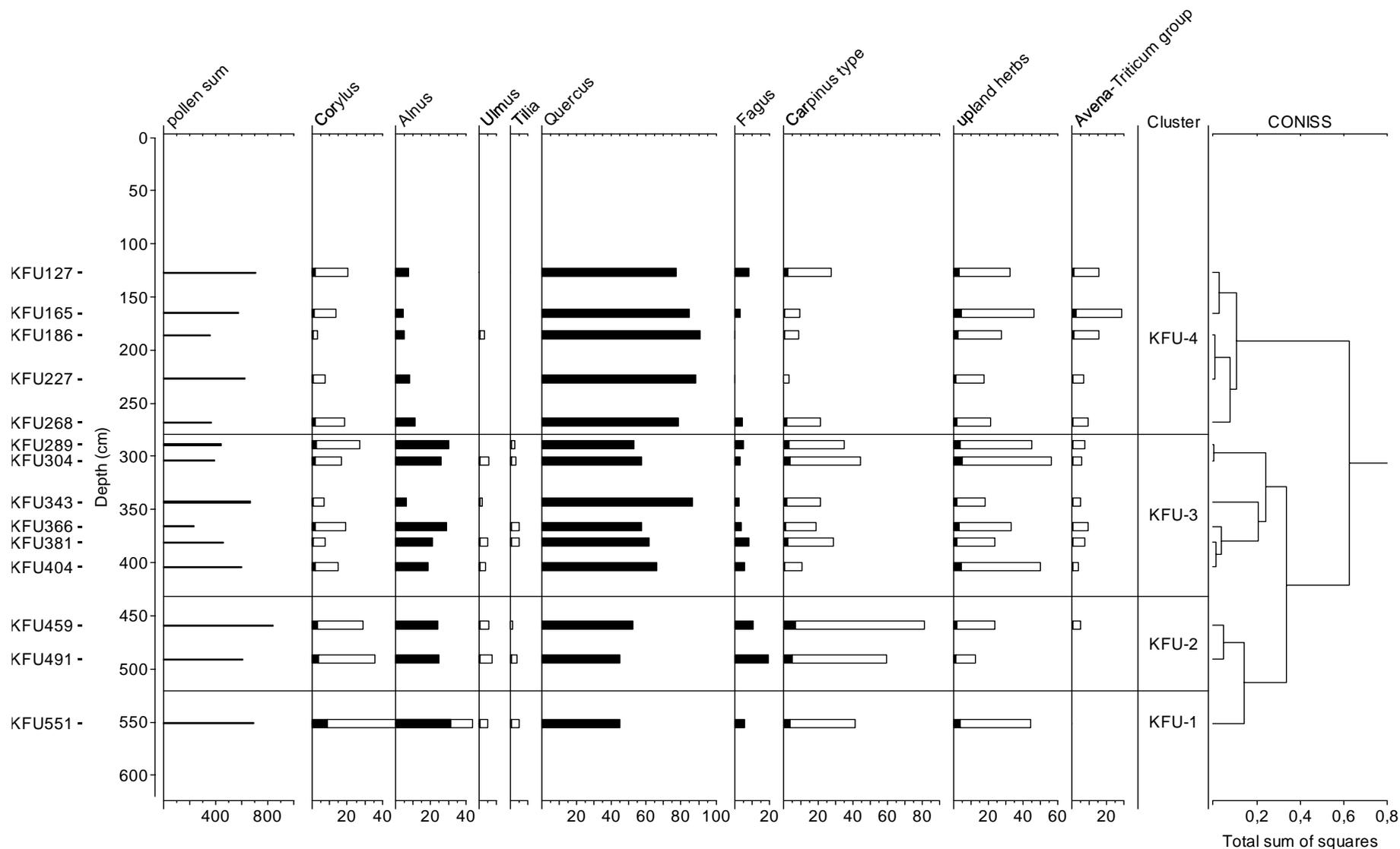


Figure 6. Upland pollen percentage diagrams for samples from the mineral soil–peat interface (KFU) at the Kreuzfenn mire, selected curves only; unshaded bars with 5x exaggeration. SALIX, PINUS AND BETULA are excluded from the pollen sums (bars not shown). Sample depths are shown in cm below the water table (\approx the mire surface). Analysis by G. Gaudig, 2000.

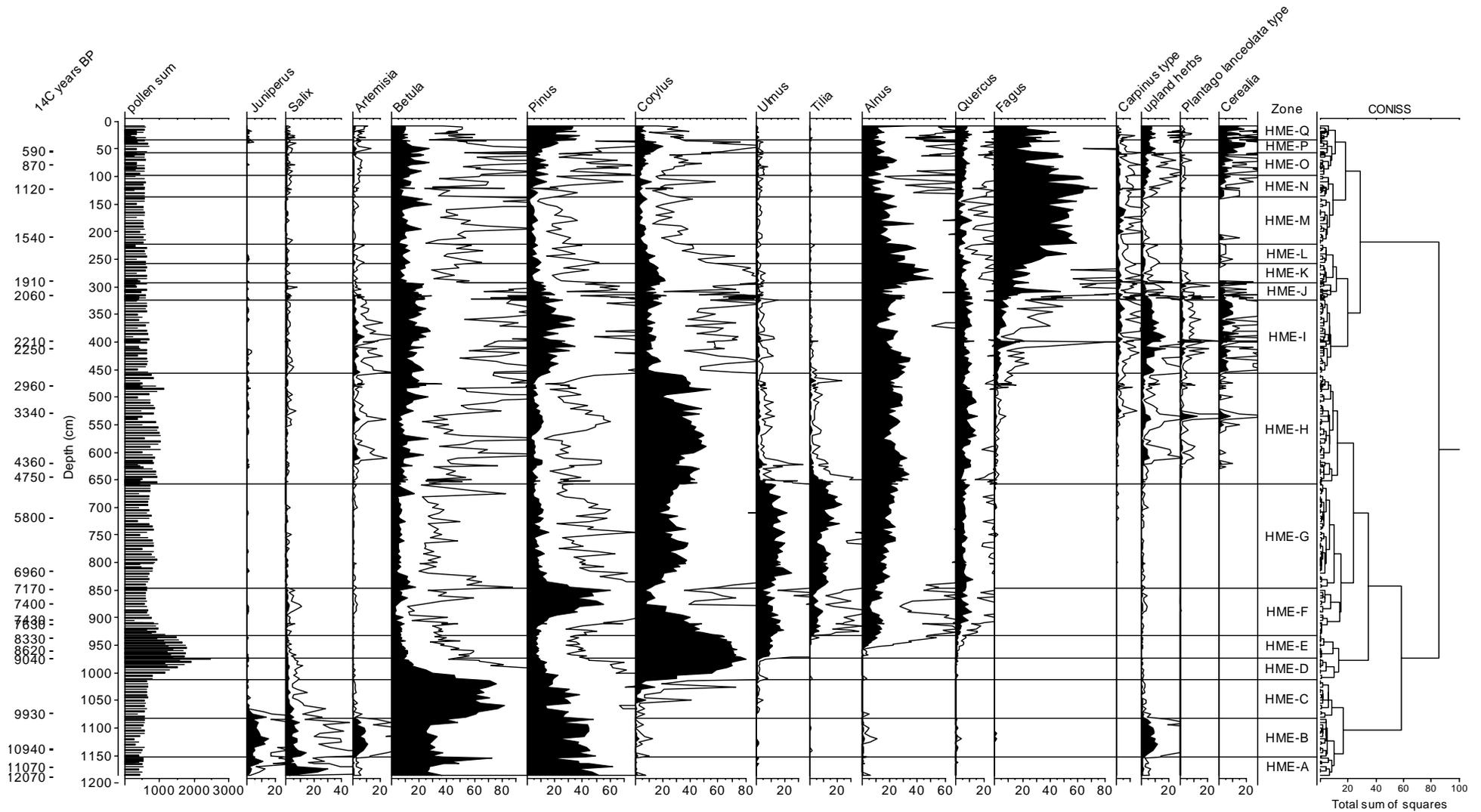


Figure 7. Upland pollen percentage diagram for the centre (HME) of the Herthamoor mire, selected curves only; unshaded curves with 5x exaggeration. Sample depths are shown in cm below the water table (\approx the mire surface). Analysis by E. Endtmann, 1998; ¹⁴C dates from Endtmann (2002).

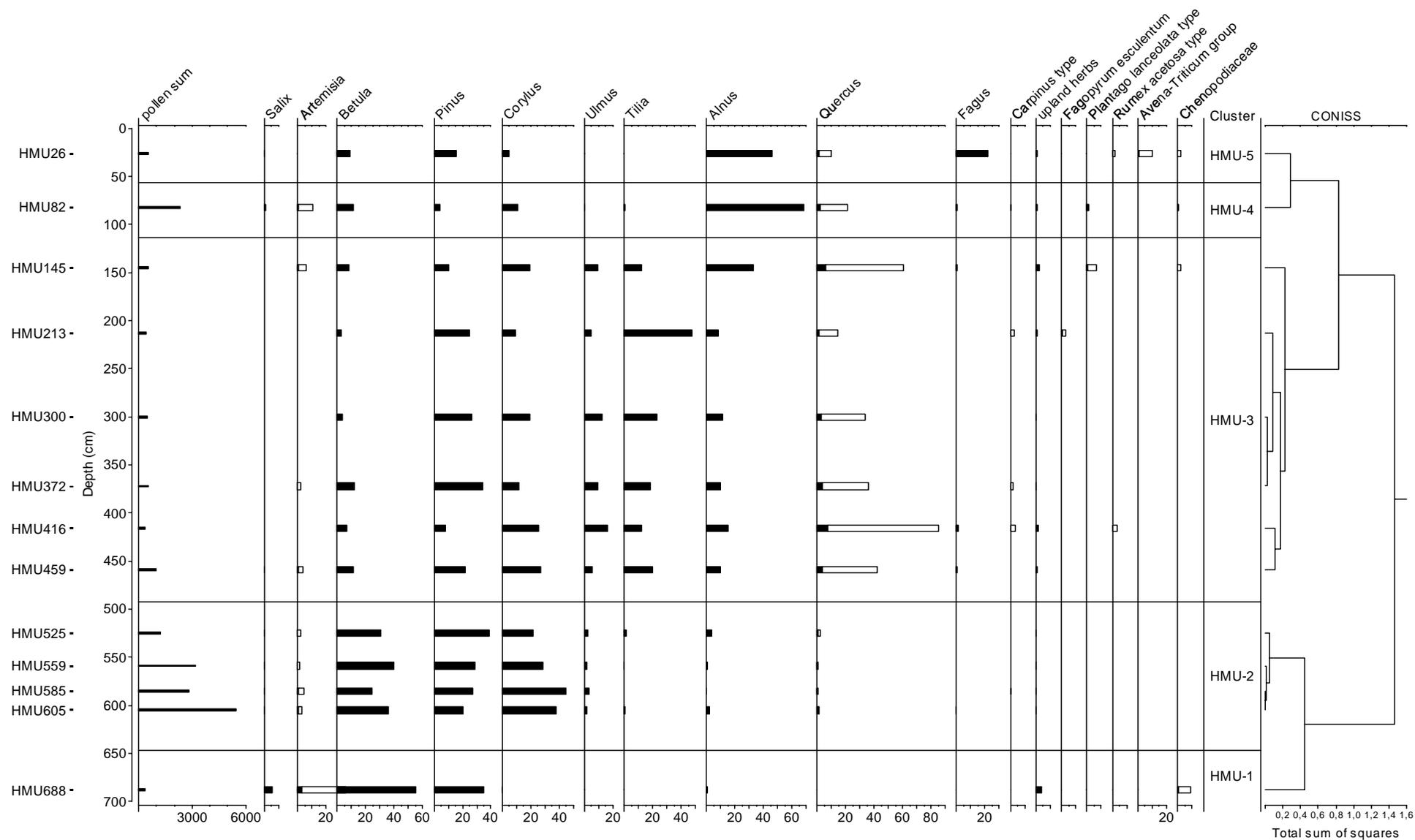


Figure 8. Upland pollen percentage diagrams for samples from the mineral soil-peat interface (HMU) at the Herthamoor mire, selected curves only; unshaded bars with 5x exaggeration. Sample depths are shown in cm below the water table (\approx the mire surface). Analysis by G. Gaudig, 2000.

the maximum value in KFG-E. When QUERCUS is removed from the pollen sum, the resulting values (data not shown) confirm an assignment to KFG-E; KFU381 hardly differs from the former sample and can therefore equally be assigned to SPAZ KFG-E. The low values of FAGUS (3%) and ALNUS (6%) and the very high value of QUERCUS (87%) in KFU343 would suggest a linkage with SPAZ KFG-F, but the upland-herbs value (2%) is too low. After excluding QUERCUS from the pollen sum, recalculated values of both KFU and KFG (data not shown) support the assignment to SPAZ KFG-E.

Cluster KFU-4 is characterised by high QUERCUS (>77%), low ALNUS (<12%), low FAGUS (<8 %) and low CARPINUS TYPE (<9 %) values in all samples, allowing assignment to KFG-F.

Herthamoor

The pollen diagram for the centre of the site (HME, Figure 7) is subdivided into 17 pollen assemblage zones (HME-A to HME-Q). The pollen values for the bottom samples (HMU samples, Figure 8) show clear differences and can be clustered into five distinct groups (HMU-1 to HMU-5).

Cluster HMU-1 consists of only one sample (HMU688), whose ARTEMISIA value is the highest of all the HMU samples (3%). Except for SALIX (5%), BETULA (55%), PINUS (35%), CORYLUS (0.3%) and ALNUS (0.3%), tree pollen types are absent. This pollen assemblage corresponds to SPAZ HME-B. JUNIPERUS was absent from the bottom samples, possibly due to bad preservation.

Cluster HMU-2 (HMU605 to HMU525) correlation options are limited to SPAZs HME-D to HME-G by the combination of high CORYLUS values (22–45%) and the absence of FAGUS and CARPINUS TYPE pollen. The small values of ULMUS (1–3%), TILIA (0–0.3%) and ALNUS (0.1–2%) suggest correlation with HME-D. Sample HMU605 is dominated by CORYLUS (38%) and BETULA (36%), PINUS reaches 20%, and ULMUS and ALNUS values are small (2%). Only single grains of SALIX, ARTEMISIA, TILIA and QUERCUS were found. Such a pollen assemblage appears in the central core (HME) only at a depth of 1,002 cm, at the transition from SPAZ HME-C to HME-D.

Cluster HMU-3 includes six bottom samples (HMU459 to HMU145) with high values of ULMUS (6–16%) and TILIA (12–23%), which limits correlation to SPAZ HME-G only. In HMU213 the very high TILIA value (47%) suggests (extra-)local over-representation. Removing TILIA from the pollen sum and re-calculating values for both HMU and HME, PINUS reaches 50%, a value that is too high for SPAZ HME-G and appears only in HME-F. ALNUS, on the other hand, reaches 20%, which is

too high for SPAZ HME-F and points to HME-G. Thus the sample cannot be unequivocally assigned to either SPAZ. Sample HMU145 has an ALNUS value of 33%, which suggests correlation with HME-H; but the ULMUS value of 6% does not support the hypothesis. The values for BETULA, PINUS, CORYLUS, QUERCUS and TILIA (all between 7% and 18%) and the small values for upland herbs (in particular ARTEMISIA and PLANTAGO LANCEOLATA TYPE) and FAGUS support assignment to the transition between HME-G and HME-H (648 cm), which has all these characteristics. However, the value for CORYLUS is slightly higher, and that of ULMUS slightly lower, than in the central core.

Cluster HMU-4 consists of only one sample (HMU82). The presence of QUERCUS and ALNUS, combined with a low FAGUS value and the absence of TILIA and ULMUS limits correlation of this cluster to SPAZs HME-H and HME-I (where TILIA and ULMUS show negligible values). The ALNUS values are higher than any value in the diagram from the central core (68% vs. 51% in HME-K), pointing at an (extra-)local over-representation. Yet the fact that CORYLUS has a distinctly higher value than PINUS restricts assignment of HMU82 to HME-H.

Cluster HMU-5 consists of only one sample (HMU26), in which FAGUS occurs at 22% and ALNUS at 46%, a combination also found in HME-K. The presence of CEREALIA (1%), which is largely absent from HME-K, makes an assignment to that SPAZ uncertain, however. Assuming over-representation and removing ALNUS from the pollen sum leads to a FAGUS value of 40%. Such a value is also found among the uppermost seven SPAZs (adjusted pollen sum). HME-K, HME-L, HME-M and HME-O can be excluded because the CEREALIA value in those SPAZs is too low (maximum of 0.9% against 1.7% in HMU26). SPAZ HME-N is disqualified by its lower PINUS value (maximum 16% compared with 30% in HMU26). This limits the possibilities to SPAZs HME-P and HME-Q. A clear assignment between the two is not possible.

DISCUSSION

Ideally, the isochrones should have been reconstructed on the basis of unconstrained cluster analysis involving all the samples (i.e. bottom and central-core samples) from each mire. However, this approach yielded hardly any groupings that shared bottom and central-core samples, and distinctly separated a large proportion of the bottom samples from most of the central-core samples. This was largely due to (extra-)local pollen deposition effects, which vary not only between the (constrained)

clusters described above, but also within them. Furthermore, even where (extra-)local effects were negligible, the samples from the central core were not sorted into groups corresponding to the SPAZs by an unconstrained clustering method. As our aim was to demonstrate that all the bottom samples belong either to one SPAZ or to several consecutive SPAZs, the use of a constrained clustering method is legitimate.

Grosse Wiese

Despite the fact that only eight of the GWU samples could be assigned to GWL SPAZs, the reconstructed isochrones clearly run horizontally (Figure 9a). The mire certainly developed as a self-sealing kettle hole mire from SPAZ GWL-Hd upward. Before that, the picture is less clear. The seven unattributed samples may all have originated in a self-sealing kettle hole mire during the period represented by SPAZ GWL-H, which spans the same depth range as the GMU samples. Alternatively, the Grosse Wiese may have grown as a floating-mat terrestrialisation mire up until GWL-Hd. The peat in bottom samples GWU493 to GWU285 could then have originated in any of the SPAZs GWL-B, GWL-D and GWL-F. Otherwise, these bottom samples may belong to different subsequent SPAZs, in which case the mire would have grown up as a mixture of self-sealing mire at the margins and floating-mat terrestrialisation mire in the centre of the basin (“kettle hole lake”, *cf.* Succow 2001). In that case, however, one would expect to find bottom samples corresponding to the other SPAZs (GWL-C, GWL-E and GWL-G), since the differences in depth between the subsequent GWU samples are not very large. As macrofossil evidence of floating-mat terrestrialisation is lacking from the central core, it is most probable that all of the uncorrelated GWU samples originated in a self-sealing kettle hole mire and should be assigned to SPAZ GWL-H.

Kreuzfenn

The isochrones run more or less parallel to the mire surface (Figure 9b). A more detailed resolution within the samples assigned to SPAZs KFG-E and KFG-F cannot be made. It is striking that, for SPAZ KFG-F, the samples of the central core span a smaller depth range than the bottom samples assigned to this SPAZ. This could arise from temporary (e.g. seasonal) lowering of the water level in the surface peat, whose weight (when no longer supported by buoyancy) causes compaction of the deeper peat layers (Stegmann *et al.* 2001) which in turn rest on the incompressible mineral substrate. Another explanation could be rapid self-sealing and rapidly rising water levels during this period,

leading to floating-mat terrestrialisation at the centre of the basin (“kettle hole lake”, *cf.* Succow 2001). The latter hypothesis is supported by the presence of peat formed from *Sphagnum* Section Cuspidata in the central core.

Herthamoor

As the bottom samples can be assigned to consecutive SPAZs (Figure 9c), the water level must have risen, indicating self-sealing of the basin. Bottom samples can be assigned to different SPAZs even during the period when lake sediments were accumulating in the central core (SPAZ HME-B and HME-D), indicating that the water level was already rising when open water was still present in the basin. This suggests a “kettle hole lake” with a self-sealing mechanism similar to that of the “kettle hole mire” (Succow 2001). Self-sealing and floating-mat terrestrialisation probably occurred in combination in this lake; as no bottom samples were assigned to HME-E and HME-F, it is likely that floating-mat terrestrialisation dominated during this phase.

In the central core, one metre of *Sphagnum* Section Cuspidata peat directly overlies the brown-moss peat in the lower part of SPAZ HME-G. The similarity of the five bottom samples assigned to SPAZ HME-G could indicate that they were formed synchronously in a floating mat. The pollen picture of that SPAZ is, however, so monotonous that the evidence is not conclusive. Another indication of floating-mat terrestrialisation is found in the five bottom samples assigned to HME-G (HMU459 to HMU213), which span a larger depth range than the SPAZ HME-G in the central core (*cf.* Figure 1). This phenomenon might alternatively have been caused by compaction, as suggested for the Kreuzfenn.

No bottom samples could be assigned to the seven SPAZs HME-I to HME-O, which points to floating-mat terrestrialisation. The space for deposition of these SPAZs was probably created by subsidence of the previously-formed peat (SPAZs HME-A to HME-H) as a result of karst (*cf.* Paulson 2001). This would also explain why the isochrones are inclined towards the deepest part of the basin, rather than horizontal as is typical for the self-sealing mechanism.

Lange *et al.* (1986) date the origin of the Herthasee, a lake bordering the Herthamoor, at *ca.* 1500 BP and suggest that the lake basin was formed by subsidence (“Erdfallsee”). Comparison of the pollen diagrams for Herthasee (Lange *et al.* 1986) and Herthamoor (HME) shows that this date must be corrected. The combination of a peak of GRAMINEAE, CYPERACEAE and upland-herb pollen with low FAGUS values at a depth of *ca.* 70 cm

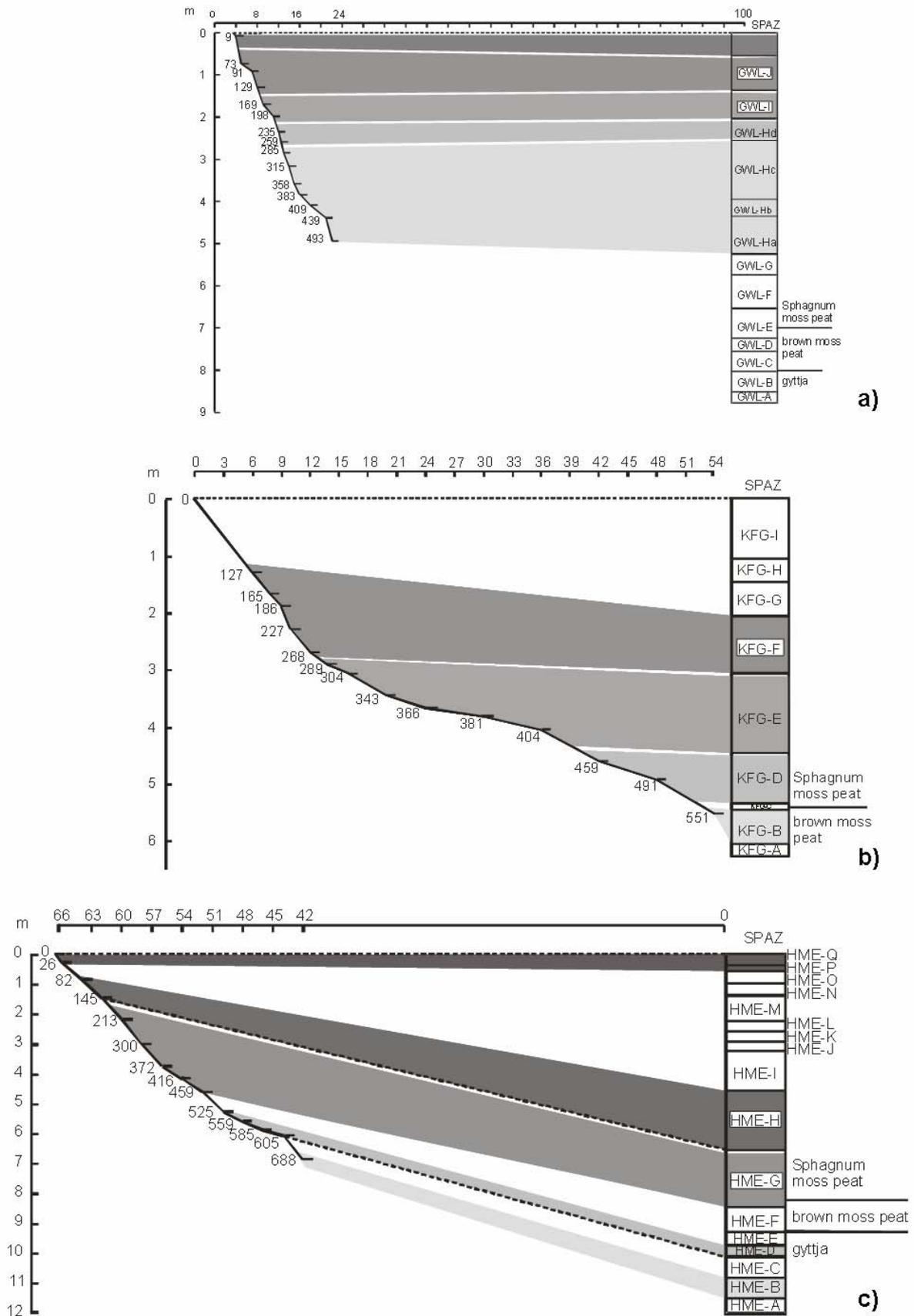


Figure 9. Isochrones for a) the Grosse Wiese mire, b) the Kreuzfenn mire and c) the Herthamoore mire. No isochrones have been reconstructed for the white areas; dashed lines denote exact assignments.

above the mineral substratum in the Herthasee diagram is also found in HME-I. This indicates that the Herthasee originated at the same time as the sinking of the Herthamoer during HME-H (*ca.* 5100-2600 cal BP, Endtmann 2002).

The assignment of sample HMU26 to SPAZ HME-P or HME-Q implies that the Herthamoer has been growing upwards since the deposition of that sample. Apparently the phase of floating-mat terrestrialisation was followed by a renewed phase of self-sealing, as indicated by the surface-parallel isochrones in the uppermost part of the mire.

CONCLUSION

All three of the mires in kettle hole-shaped basins that were investigated show surface-parallel peat isochrones, demonstrating that their water levels have risen considerably during peatland development. The rising water levels are confirmed by (extra-)local pollen values of *QUERCUS* and *TILIA* in various bottom samples, which indicate that upland tree species once grew near the former mire margins.

Such steadily rising water levels and consequent "bottom up" peat accumulation in basins that are disconnected from the regional groundwater could also arise if the climate was becoming continuously wetter, but this scenario is contradicted by palaeoclimatic data (Barber *et al.* 2004, Moberg *et al.* 2005). The rapid and regular upward growth is a strong indication of the existence of an internally controlled "kettle hole mire" mechanism based on the process of self-sealing. In the case of the Herthamoer, the process of upward growth alternated and was combined with floating-mat terrestrialisation following subsidence of the basin, probably as a result of karst.

A gradual rise in water and surface levels is a normal process in the development of peatlands with continuous water inflow (Sjörs 1948, Kulczyński 1949, Heinselman 1970, Joosten & Clarke 2002). However, whereas rising water levels are generally *caused* by accumulating peat damming up water to progressively higher levels (Ivanov 1981), in the case of the "kettle hole mire mechanism" peat accumulation *follows* the rise in water level that results from sealing-off of the mineral floor of the basin. Whereas the limited hydraulic conductivity of the peat is a prerequisite for peatland growth and expansion in other situations, a kettle hole may be filled with highly conductive peat or even – in the case of kettle hole lakes – with open water.

The fact that evidence for the "kettle hole mire

mechanism" was found at all three of the sites investigated in this study suggests that, although generally disregarded, it may actually be a common peat-forming mechanism in kettle hole-shaped basins worldwide.

The high *Sphagnum* peat accumulation rates in kettle hole mires (Couwenberg *et al.* 2001) are of particular interest in the context of *Sphagnum* cultivation for horticultural uses (Gaudig & Joosten 2002). Artificial progressive raising of the drainage level to simulate self-sealing may prove to be a viable option for maximising *Sphagnum* yields.

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