CHAPTER III

Climatological, stratigraphic and palaeo-ecological aspects of mire development

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Introduction

In chapter 2 of this volume, Pons (1992) described in broad outline the Holocene development of large mire complexes in the western and northern Netherlands. He devoted special attention to the alternation of peat and clay deposits in the Dutch coastal region as a reflection of the marine and fluviatile sedimentation history and of edaphic and hydrological influences. In this chapter we shall first concentrate on climatological patterns in relation to mire formation, in both a temporal and spatial perspective. The aim of this chapter is also to outline other palaeo-ecological factors that determine mire formation. In a case study we shall focus our attention on the mire formation of one particular raised bog area, the Bourtanger Moor in the northeastern Netherlands (Fig. 1). The development of mire in this area since the late Pleistocene will be described on the basis of stratigraphic studies. Much attention will be paid to the analysis of peat-growth mechanisms and the hydrological changes in the course of mire development.

In this chapter the term 'mire' is used for what in most other palaeobotanical papers concerning peat stratigraphy and bog development generally is called 'bog' or 'peat bog'. This is done for the sake of consistency with the other chapters of the book.

3.1. Climatological aspects of mire development

3.1.1. *Climate – its general significance for mire formation, with special reference to raised bogs*

Bogs develop in the landscape in damp or wet places where accumulation of organic material can take place. The accumulation of organic material is the net result of the production of plant material by the vegetation and the decomposition of this material by micro-organisms. The rate of decomposition of the organic material is regulated to a large extent by temperature, water and oxygen supply, pH, the chemical composition of the plant material and the species composition of the micro-organisms.

Mires can only develop on water-saturated soils or in shallow, stagnant waters (Clymo 1983; Moore 1984, 1986). A state of saturation by water is often the result of specific climatic con-

J. T. A. Verhoeven (ed.). Fens and Bogs in the Netherlands: Vegetation, History, Nutrient Dynamics and Conservation, 81–129.

Fig. 1. Bourtanger Moor to the east of Emmen: peat section at Klazienaveen, with global datings of a number of important developments in peat growth, in (uncalibrated) ^{14}C-years BC. The height of the section is 3.10 m. The location of this peat section is indicated on the map of Fig. 10 with an asterisk on the line A....B.

5200 BC: beginning of the ferruginous seepage; 4500 BC beginning of the deposition of siderite, bog iron-ore, in the seepage peat; 3100 BC: sudden ending of the seepage, desiccation of the seepage peat with forming of drying-cracks (one crack is visible on the photo), and soon after this the start of ombrogenous peat growth; 2500 BC: drying-out of the ombrogenous *Sphagnum*-peat, caused by vertical water losses of a bog area of 4–6 hectares; 2000 BC: first growth of *Sphagnum imbricatum* and *S. papillosum* peat (which cannot become established for very long at the spot in question) in the damper highly humified *Sphagnum* peat; 1500 BC: beginning of the forming of a raised-bog lake in a west-east contact zone; 1200 BC: expansion of the bog lake over a surface of about 20 hectares; 800 BC: dry period of short duration with serious drying-out of the bog lake; 500 BC: bog burst, draining of the bog lake towards the east, leaving an eroded bog surface of many hectares; beginning of the large-scale growth of fresh to poorly humified *Sphagnum* peat in this area; 100 BC: the surface of this part of the bog is fully overgrown by poorly humified *Sphagnum* peat. Further explanation of these phenomena is given in section 3.2. of this chapter.

ditions: precipitation, evaporation, mean temperature, solar radiation, etc.

Geographic differences in climatic conditions and the related distribution of different types of mires in Europe have been well described by Eurola (1968), Moore & Bellamy (1973), and Overbeck (1975), and others. Frenzel (1983) indicates that climatic factors are perhaps only prohibiting for peat formation in the subarctic, the subalpine and the steppe regions of Europe. In the marginal areas of the distribution of bogs, water-saturated conditions can only exist in depressions and only if precipitation exceeds evaporation in the catchment areas surrounding these depressions.

With reference to the temporal aspect, two important periods can be indicated during which mire formation was initiated or stimulated as a result of climatic factors in northwestern Europe after the Late Glacial period (to c. 8000 BC,

Table 1. Zonations and periods in the Weichsel Late Glacial and the Holocene. In Roman numerals: according to Jessen (1935) & Iversen (1949). The datings are derived from non-calibrated ^{14}C dates. This zonation is also used in Fig. 6.

	Period	Zone	Age (AD/BC)
HOLOCENE	SUBATLANTIC	IX	AD 0 BC; 1000
HOLOCENE	SUBBOREAL	VIII	2000; 3000
HOLOCENE	ATLANTIC	VII	4000; 5000
HOLOCENE	BOREAL	VI, V	6000
HOLOCENE	PREBOREAL	IV	7000; 8000
LATE GLACIAL	LATE DRYAS	III	9000
LATE GLACIAL	ALLERØD	II	10000
LATE GLACIAL	OLDER DRYAS	I	
LATE GLACIAL	BØLLING		11000
WEICHSEL GLACIAL			

Table 1). The first period spans the Preboreal (c. 7000 BC) until the beginning of the Boreal (c. 6500 BC). Prior to this period the mean temperature rose by about 4°C (Taylor & Smith 1980). As a result of this sharp rise in temperature large parts of the ice sheet melted, a large quantity of moisture was taken up into the atmosphere and the water table rose. Thus, mires were able to develop in low-lying parts of the landscape, which became saturated by water.

A second climatic change that was important for mire formation occurred around 5000 BC, at the beginning of the Atlantic. In this period, raised bogs started to form as a result of high precipitation. Broadly speaking, climatic conditions suitable for the formation of raised bogs have prevailed since the Late Glacial up to the present day.

Although climatic conditions play a dominant role in the water supply of mires, other hydrological circumstances are also important in this respect. Notably the local availability of groundwater and surface water play a role. A few examples of such influences are indicated in Table 2. Here we are dealing with different types of fen or minerotrophic mire.

A supply of groundwater or surface water is totally absent in the case of raised bogs. These ombrotrophic bogs are fed exclusively by precipitation, which means that there must be sufficient rain water available over a certain period or even throughout the year to prevent the bog from drying out at all or even for a short time. Evaporation plays a dominant role in the moisture loss from raised bogs. With higher rates of evaporation, as generally prevail in warmer countries, a moisture deficit is more likely to occur. There-

Table 2. Some hydrological characteristics of different types of mire.

Mire type	Characteristic hydrological conditions
fen mire	– peat formation occurs as a result of the gradual rising of the groundwater level in the surroundings, with becoming permanently waterlogged;
floating mats	– peat formation occurs in a pool or lake;
flat plane mire	– peat formation occurs as a result of regular flooding;
seepage mire	– peat formation occurs as a result of recharge water from a water-bearing layer;
valley bog	– peat formation occurs where surface water flows over a slope.

fore, in warmer regions precipitation will have to be more abundant in order to ensure sufficiently damp conditions for the growth of raised bog. The prevailing temperature is an important factor in determining the intensity of evaporation.

It will be clear that the distribution of raised bogs is much more closely linked to certain climatic limiting conditions than is the case with fen mires. For this reason and as relatively much is known about the relation between climate and the occurrence of raised-bog formation, we shall focus our attention here specifically on ombrotrophic bogs.

In the first part of this chapter we shall concentrate on the climatological limits for raised-bog growth on the basis of the present-day distribution in Europe (3.1.2.). Subsequently, in 3.1.3., attention will be devoted to climatic fluctuations in the Netherlands since the beginning of the formation of raised bog in the Atlantic period (c. 5000 BC) until the present day (AD 1900–1950), with special reference to climatic changes as indicated by palaeobotanical data and peat-stratigraphic research.

3.1.2. *Climate and raised bog in Europe: a spatial perspective*

3.1.2.1. *Distribution and types of ombrotrophic mires in Europe*

Before focusing our attention on the distribution and types of ombrotrophic bogs in Europe, we present in Table 3 an overview of the types of climate in which the various types of raised bog occur, with details of the characteristics of each climate type.

These climate characteristics are derived from the 'Handbuch ausgewählter Klimastationen der Erde' (Müller 1980). The table shows that climatic conditions for raised bog growth within Europe vary considerably. Moore and Bellamy (1973) give a clear survey of the occurrence of types of raised bog in Europe (Fig. 2).

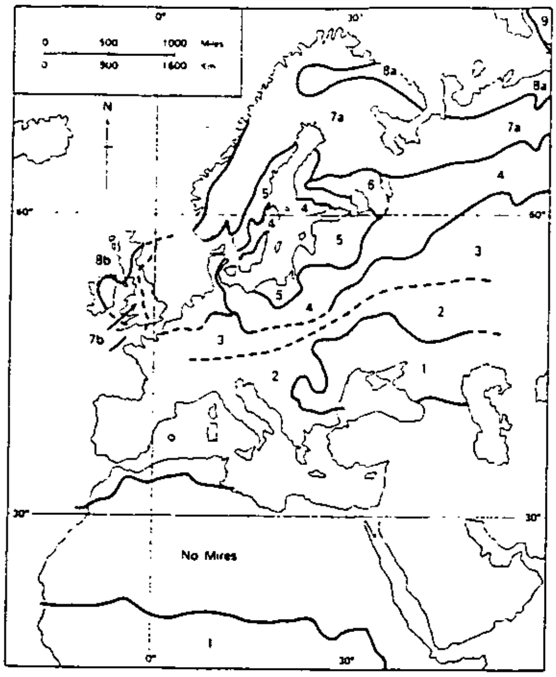
In our description of the various types of ombrotrophic bogs in Europe and their distribution in relation to climate, we restrict ourselves to the lowland raised bogs (below c. 200 m above mean sea-level). In the case of the montane raised bogs the climatic conditions for ombrogenous peat formation are realized in a completely different way.

Plateau-type or lens-type raised bogs. These raised bogs are best developed in central Ireland and also in western Norway, England, the Netherlands and Germany. In Poland, Denmark, southern and southeastern Sweden and southwestern Finland they grade into concentric raised bogs. In Ireland and Scotland there are transitions to blanket bogs.

The plateau-type raised bogs have a characteristic slightly domed relief (lens-shaped). The centre of the mire surface is almost flat. These characteristic features account for the name plateau-type, lens-type or domed raised bog. In the Dutch literature they are also known as 'vlakhoogvenen' (Barkman & Westhoff 1969).

Table 3. Some characteristics of climate types of the temperate zone, after Müller (1980).

climate type	annual fluctuation in air temperature (°C)	mean temperature coldest month (°C)	mean temperature warmest month (°C)	no. of months with frost	period with maximum intensity of precipitation
Oceanic	<16	>2	<20	0	autumn/winter
Suboceanic	16 to 25	2 to −3	<16	0	autumn/winter
Subcontinental	20 to 30	−3 to −13	>20	4	summer/autumn
Continental	30 to 40	−10 to −20	15 to 20	4 to 5	spring
Continental Boreal	20 to 40	−15 to −20	10 to 20	5 to 7	winter



1 = valley bogs and flooded fens; 2 = tertiary valley mires; 3 = continental raised bogs; 4 = plateau raised bogs; 5 = concentric raised bogs; 6 = eccentric raised bogs; 7a = aapa fens; 7b = ridge raised bogs; 8a = palsa bogs; 8b = blanket bogs; 9 = Arctic bogs.

Fig. 2. Distribution of types of mires in Europe. After Moore & Bellamy (1973).

The plateau-type raised bogs are situated in the Oceanic, the Suboceanic and the Subcontinental climate types, which belong to the temperate climatic zone of the world. The Netherlands are situated at the transition between the Oceanic and the Suboceanic climate.

Well-developed plateau-type raised bogs occur in regions with a high effective humidity, usually with a relatively high precipitation between c. 700 and 1150 mm/year (Schouten 1984; Overbeck & Happach 1956). These conditions occur in Ireland, England, western Norway, the Netherlands and northwestern Germany. The raised bogs in these countries show a tendency to expand beyond the original depressions in which they first developed. Such expansion can lead to the merging together of raised bogs over relatively low ridges that formerly functioned as watersheds between areas of raised bog. The less well developed plateau-type raised bogs are to be found in Poland, Denmark, southern and southeastern Sweden and southwestern Finland. In these regions the annual precipitation is often lower than 700 mm (Von Post & Granlund 1926). There the effective humidity (precipitation minus evaporation) is just sufficient to maintain the raised bogs, on account of the period of frost of 1–3 months in the winter half-year. The development of raised bogs in those regions is restricted to depressions.

Blanket bogs. These raised bogs occur in Ireland and Scotland. The characteristic feature of these bogs is that they are able to expand over the landscape like a blanket; the occurrence of these raised bogs is thus not limited to depressions in the landscape. Slopes with a gradient of up to c. 25 degrees may be covered by this type of bog (Schouten 1984).

Blanket bogs are to be found exclusively in the Oceanic type of climate in areas with annual precipitation between 1250 and 2000 mm (Schouten 1984).

Aapa fens. These mires occur in central Norway and Sweden, central Finland and north-European Russia. An aapa mire resembles to some extent a fen. The development of aapa fens only occurs on a small scale in hydrologically favourable circumstances, where the surplus precipitation can only run off slowly. These mires occur in the Continental Boreal climate. The precipitation is less than 500 mm much of which becomes available in spring as a result of the melting of snow and ice.

Palsa bogs (*Arctic bogs*). These are ombrotrophic mires on permafrost, often with a frozen nucleus. They reach a height of about one metre, on average; they generally measure several tens of metres in diameter. The surrounding tundra soil is usually waterlogged in the vegetation period. These bogs occur in Norway, Sweden, Finland and Russia, north of the Arctic circle.

Concentric raised bogs (*Baltic raised bogs*). Concentric raised bogs are found in northern Poland, the Baltic States, in Russia, southern Finland and eastern Sweden. If the effective humidity is sufficiently high and there is also a favourable growing season, the raised-bog nucleus grows upward and thus develops a convex profile. In Finland this is called a kermi raised bog. Such kermi raised bogs are characterized by rings of hummocks and hollows which are situated concentrically around the highest, central part of the bog.

Concentric raised bogs are to be found in the Subcontinental type of climate. In the winter these bogs are frozen and covered with snow. Consequently a considerable quantity of water becomes available when the snow melts in spring, before the vegetation develops.

Wooded raised bogs (*Continental raised bogs*). These bogs occur in northeastern Poland and central-European Russia. They are usually plateau-type or concentric raised bogs covered by forest for the most part or covered by clumps of trees. Bogs of this type are situated in the Subcontinental and Continental climate region.

3.1.2.2. *Climatological limits for ombrogenous peat growth, going from western to eastern Europe and with special reference to the situation in the Netherlands*

The raised bogs in Ireland and northwestern Germany and the countries in between are located in areas with a strongly to moderately oceanic climate. One of the characteristics of this type of climate is that the mean monthly temperature is always above 0°C, as a result of which a precipitation surplus is present almost throughout the entire year. For a number of raised bogs along a west-east gradient in Europe, the figures for annual precipitation and evaporation are plotted in the graph shown in Fig. 3. This Fig. is based on investigations carried out on the water balance of bogs in Ireland (Burke 1975), northwestern Germany (Eggelsmann 1981) and European Russia (Romanov 1968).

From this graph it is evident that the evaporation is more or less the same in bogs in Ireland and northwestern Germany, amounting to 450–550 mm per year. This means that the evaporation rate in raised bogs in the Netherlands must be in the same order of magnitude, as they are located in between these two. An estimation of the water balance for De Grote Peel bogs (Joosten & Bakker 1988) (evaporation 483 mm in 1985/86) is in agreement with this. Fig. 3 further shows that there is a great difference between Ireland and northwestern Germany in terms of the annual precipitation. In the Irish blanket bog region the precipitation amounts to 1100–1450 mm/year, whereas it is much lower in northwestern Germany, amounting to 690–825 mm/year. In Germany, in some years the water balance may show a precipitation deficit, as indicated by an asterisk in Fig. 3.

Thus, in the years when there is a net deficit in the water balance there will be a persistent shortage of moisture, that will only be neutralized in years with relative abundant precipitation and/or little evaporation. Under conditions of moisture shortage the growth of peat slows down and if it is persistent then peat growth even comes to a standstill. The limit of precipitation below which a permanent moisture shortage will occur is probably slightly less than c. 700 mm per year for the raised-bog region in Germany. Because comparable climatic conditions prevail in the Netherlands, there the formation of raised bog will also occur where the mean intensity of precipitation is not less than c. 700 mm per year.

Finally, it is evident from Fig. 3 that precipitation values lower than 700 mm per year are recorded in the raised bogs of European Russia. This is closely connected, however, with the deviating climatic conditions there. These raised bogs are situated in a region with a continental climate characterized by cold winters, during which the temperature is below freezing point for several months. In the areas investigated, discharge occurs only in the months from May until September. There the growth of raised bogs is more dependent on the time of year at which the ice and snow begin to melt. Consequently, in European Russia a high rate of evaporation throughout the year, like that occurring in western Europe, is seldom attained.

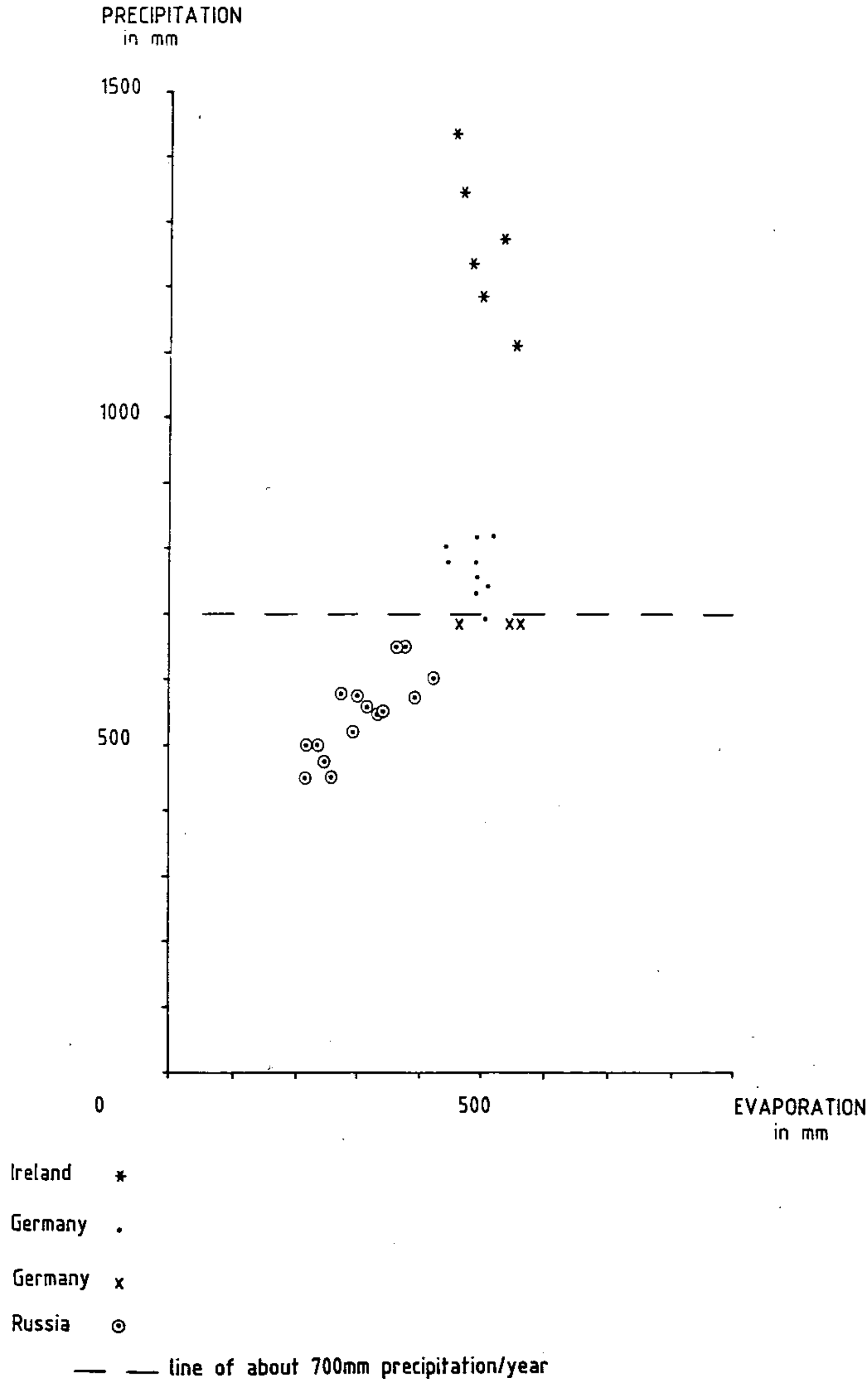


Fig. 3. Relation between precipitation and evaporation in raised bogs in Ireland, northwestern Germany and Russia.

The distribution of lens-type raised bogs in the oceanic climate zone of western Europe is related to the mean annual precipitation, for which there is not only a lower limit but probably an upper limit too. For the raised bogs in Ireland this upper limit is c. 1250 mm per year (Schouten 1984). Above this level the 'lenses' become invisible and there is a transition to blanket bogs.

It is clear that the mean precipitation surplus of the (lens-type) raised bogs in Ireland is much greater than in northwestern Germany. According to Fig. 3 the precipitation surplus in Ireland amounts to 350–700 mm per year, while in northwestern Germany it is only 150–275 mm per year. In the raised-bog region of European Russia the precipitation surplus amounts to 200–250 mm per year, this being in the same order of magnitude as in the Netherlands and northwestern Germany.

3.1.2.3. *The distribution of raised bogs in the Netherlands in relation to climate*

From the above it is evident that raised bogs in the strongly to moderately oceanic climate zone of western Europe occur under widely different conditions of mean annual precipitation. The variations in the mean annual temperature and quantity of evaporation in this zone are small. As the evaporation in intact raised bogs in the Netherlands has not been measured, the distribution of raised bogs in the Netherlands in relation to climatic factors has only been related to mean precipitation and mean temperature.

In Fig. 4 an overview is presented of the distribution of raised bogs and fen mires in the Netherlands (Casparie 1986a) for the time just before large-scale land drainage was carried out. For raised bog the situation c. AD 1500 is indicated. The distribution of fen mires corresponds more closely to the situation in the 19th and 20th century. Consequently, the submerged raised bogs of the western Netherlands are designated fen mires here and the vanished peatlands in the IJsselmeer region and Zeeland are not indicated. Also the mires beyond the present-day coastline (that no longer exist) are disregarded here.

For the areas where raised bogs were formerly present (Fig. 4) or where partly dug-off relicts of raised bog remain, the mean annual precipitation and mean annual temperature for the period 1950–1980 are shown in Table 4.

On the basis of the information given in section 3.1.2.2. and the distribution of raised bogs as shown in Table 4 it can be assumed that a mean annual precipitation of c. 700 mm or more and a mean annual temperature of at most 9.5°C (with a mean July temperature of 16–17°C) are important conditions for raised bog growth.

3.1.3. *Climate and raised bog: a temporal perspective*

3.1.3.1. *Climatic fluctuations from the beginning of raised-bog formation until the present day*

Lamb (1977) presents an extensive overview of the history of the climate during the Holocene in England and Wales, in which he gives an esti-

Table 4. Mean annual precipitation and mean annual temperature for areas of former raised bog or relicts of raised bog in the Netherlands.

Raised bog areas	Mean annual precipitation (mm)	Mean annual temperature (°C)
Bourtanger Moor	730–770	8.6
Smilderveen	835–840	8.7
Friezenveen	805–820	8.8
Bogs on the Drenthe-Overijssel border	765–810	8.9
Engbertsdijkveen	765	8.9
Haakbergerveen	763	8.9
Bogs in the Gelderse Vallei	770	9.1
De Peel	700–725	9.4

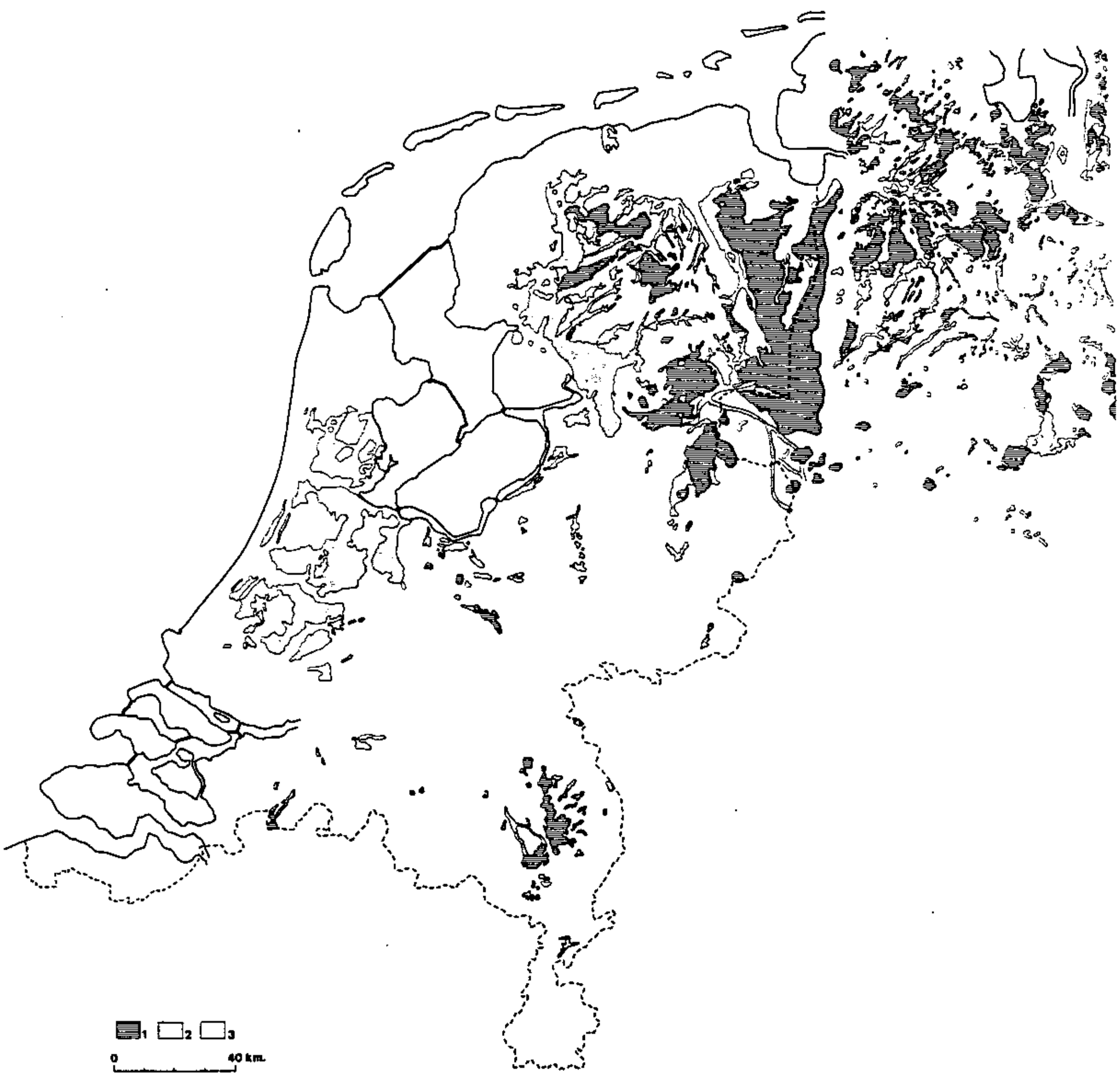


Fig. 4. Distribution of raised bog (c. AD 1500) and fen mire (c. AD 1900) in the Netherlands. 1. raised bog; 2. fen peat; 3. other soils.

mate of the course of temperature and moisture levels (precipitation and evaporation) from the beginning of the formation of ombrogenous peat in the Preboreal (c. 7000 BC) until the present day (AD 1900–1950). He used many different scientific sources, which will not be discussed here. The method of estimation is based on analyses of meteorological data from the past (i.a. data for temperature and precipitation, frequencies of different types of reports of weather conditions, wind circulation patterns on a wide scale in the past). The evaporation is estimated from an empirical formula given by Turc (Lamb 1977); for this estimation it is necessary to know the precipitation and the approximate temperature.

The climatic development since the Late Glacial, as given by Lamb for Wales (see Table 5), clearly shows fluctuations in precipitation, temperature and thus also atmospheric humidity.

Table 5. The course of temperature (T) and moisture (P = precipitation; E = evaporation) levels during the Holocene in England and Wales, after Lamb (1977). Temperature in °C, moisture in percentages of the mean values for 1900–1950.

Dating	Period	Temperature			Moisture level	
		T_{ja}*	T_{djf}*	T_{ann}*	P	E
c. 7000 BC	Preboreal	16.3	3.2	9.3	92–95	94–98
c. 6500 BC	Boreal					
c. 4500 BC	Atlantic	17.8	5.2	10.7	110–115	108–114
c. 2500 BC	Subboreal	16.8	3.7	9.7	100–105	102–104
900–450 BC	Subatlantic	15.1	4.7	9.3	103–105	97
1150–1300	Little Optimum	16.3	4.2	10.2	103–104	104
1550–1700	Little Ice Age	15.3	3.2	8.8	93	94
1900–1950	England Wales	15.8	4.2	9.4	100	100
maximum difference		2.7	2.0	1.9		

*T_{ja} mean temperature during July and August
T_{djf} mean temperature for December, January and February
T_{ann} mean annual temperature

An interpretation of the data in Table 5 gives the following result. As a general rule, there is little change in precipitation surplus over the period of 9000 years, because according to Lamb the quantity of precipitation and evaporation increases or decreases roughly proportionally with any rise or fall in temperature (see Fig. 5).

A clear exception to this general rule is formed by the situation towards the end of the Subboreal, notably at the boundary with the Subatlantic. In this period the quantity of pre-

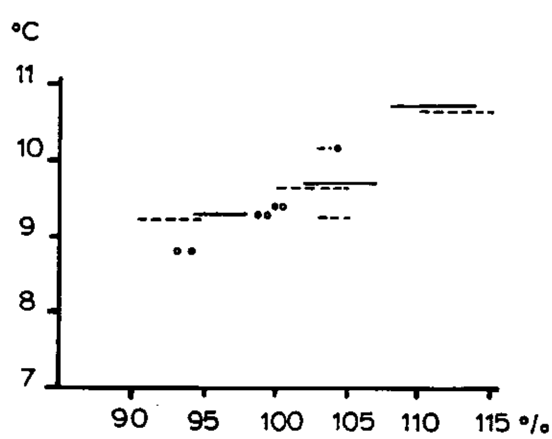


Fig. 5. The temperature change in relation to the change in precipitation and evaporation in percentages (situation from 1900–1950 is 100 %). Legend: — evaporation percentage (rough); oooo evaporation percentage (more exact); ‐‐‐ precipitation percentage (rough); ••• precipitation percentage (more exact).

cipitation is evidently higher than one would expect on the basis of the temperature curve. This period is thus relatively wetter than other periods. This development is also illustrated by the palaeobotanical research carried out by Casparie (1972) and Dupont (1985) in southeastern Drenthe, and will be dealt with in more detail in 3.1.3.2. With respect to the period 1900–1950, in the total period of 9000 years, precipitation and evaporation decrease by 8 % and 6 %, and increase by 14 % and 15 %, respectively. Although the climate is characterized in general by only limited fluctuations in temperature, a number of climatologically different periods can nevertheless be distinguished at the end of the last Ice Age. These periods are briefly discussed in the overview presented below, see also Fig. 6.

Preboreal (8300–6800 BC): a period of temperature rise, with summers as warm as or even warmer than the period AD 1900–1950.

Boreal (6800–5500 BC): continuing rise in temperature. The winters were less cold and possibly drier than at present. The summers were warmer and somewhat drier than nowadays.

Atlantic (5500–3000 BC): the warmest period of the Holocene; damper than the preceding

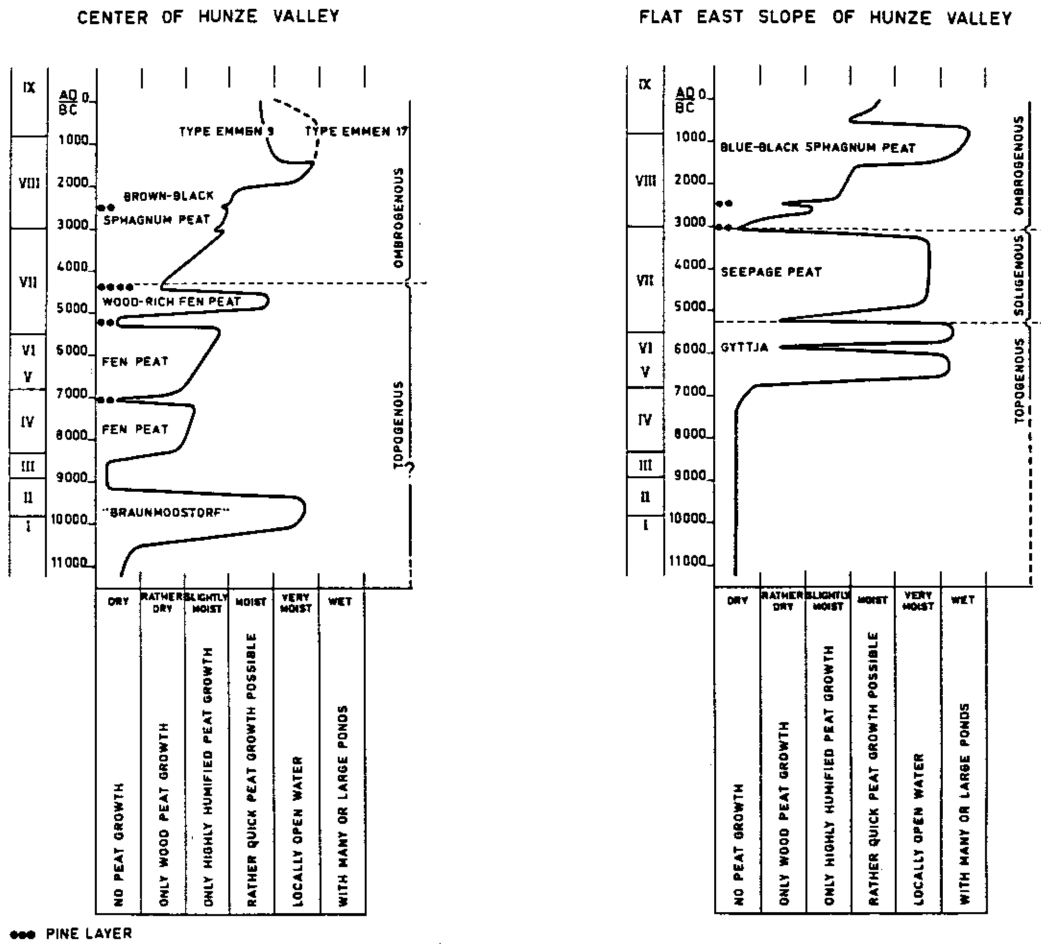


Fig. 6. The Bourtanger Moor east of Emmen. The degree of moisture is plotted against time. Left curve: the central part of the Hunze valley; right: the gradual eastern slope of the Hunze valley. The peat stratigraphy from which this information is derived is given in section 3.2. After Casparie (1972).

period. Moreover a wet period with westerly winds prevailing. There was a peak in dampness between 4000 and 3000 BC.

Subboreal (3000–800 BC): some degree of fall in temperature. The climate was characterized by somewhat greater fluctuations and until c. 2000 BC it was very dry in northern Europe. Subsequently fairly wide fluctuations in precipitation and temperature occurred, resulting in lower temperature (1°C or perhaps slightly more than at present) and more precipitation around 800 BC.

Subatlantic (800 BC until the present day): a further cooling down of the climate; mean temperature in 700–500 BC was 2°C lower than 500 years previously. Between 500 BC and AD 500 it was considerably wetter here while the following period until AD 1300 was relatively drier. Subsequently the temperature rose again slightly, but it remained a wetter period, that has continued until the present day.

For the situation in the Netherlands the general temperature fluctuation is of the same order of magnitude as in Wales, i.e. between 9 and 11°C (Dupont 1985). Consequently, the mean intensity of evaporation in the Netherlands will not have differed very much throughout time from the situation described for Wales. The same applies for the course of precipitation throughout time, although mean precipitation will have been much lower than in Wales. The surplus of precipitation in the Netherlands throughout time must have been considerably lower than in Wales.

Considering all the available information, it seems reasonable to assume that the second half of the Atlantic and the Subatlantic were periods that were very favourable for the development of raised bogs. The first half of the Atlantic, the Subboreal and the remaining part of the Subatlantic can be regarded as moderately favourable to favourable for the development of raised bogs. These conclusions are not completely in agreement with those of the peat-stratigraphic research.

On the basis of the evidence provided by peat stratigraphy, however, this view requires some modification. In the southern part of the Bourtanger Moor the formation of ombrogenous peat took place extensively during the first half of the Subboreal; in this period the Smilde bogs expanded considerably as a result of ombrogenous peat formation and in the valley of the Drentse Aa the formation of raised bog is incipient. In many former pingos a more or less ombrogenous peat deposit of Subboreal age is or has been present as well.

3.1.3.2. *Peat growth and climatic change*

Palaeobotanical/peat-stratigraphic research does not provide any direct information about the climate and climatic changes. Yet such research does provide much information about the degree of dampness of the peat-forming environment and particularly any changes in dampness. It is reasonable to assume that these changes were partly caused by some climatological influence, but no generally valid criteria can be given for this. Fig. 6 shows the development of the moisture content of the peat-forming environment in terms of the types of peat formed for two places in the Bourtanger Moor to the east of Emmen.

These sites, situated in the same area of bog, lie about 2 km apart. There are such great differences between the two curves that a direct influence of the climate on the type of peat formed, also where ombrogenous peat is concerned, is apparently minimal. Various local situations affect the peat-forming processes to some extent; a more detailed analysis of the phenomena will be necessary before anything can be said about the (direct) influence of the climate.

The dating of the beginning of raised-bog formation in as many bogs as possible can be a method for obtaining insight into the extent to which the various Holocene periods were more or less suitable for the formation of new ombrogenous peat (Joosten & Bakker 1988:139–141). The method has its limitations, as has been pointed out already, for there are many more factors involved than just the climate. Such factors include, for example, the continuation of the raised-bog formation, the environmental circumstances (the presence or absence of suitable soils, etc.) and the extent of the raised-bog formation. As the formation of peat expands over the landscape the possibility of new raised bog being formed becomes smaller. It has been assumed that in the Subboreal the climatological conditions for new raised-bog formation were less suitable than in the Atlantic because the number of new Subboreal raised bogs is small; this assumption, however, disregards the fact that the best locations for raised bog had already been occupied in the Atlantic period.

In the raised bog of Bolton Fell Moss in the west of England it has been possible to record in detail the temporal development of the moisture regime (Barber 1981). Many of these wet-dry transitions (Fig. 7) could be correlated satisfactorily with climatic changes in the last two thousand years as deduced from other sources. The raised-bog vegetation appears to react fairly rapidly to changes in temperature and precipitation.

The detailed information on peat stratigraphy that has been collected in the Netherlands (Casparie 1972; van Geel 1978; Dupont 1985) indicates that the formation of ombrogenous peat took place from c. 4000 BC until into the Middle Ages, at least in the northern Netherlands. It is

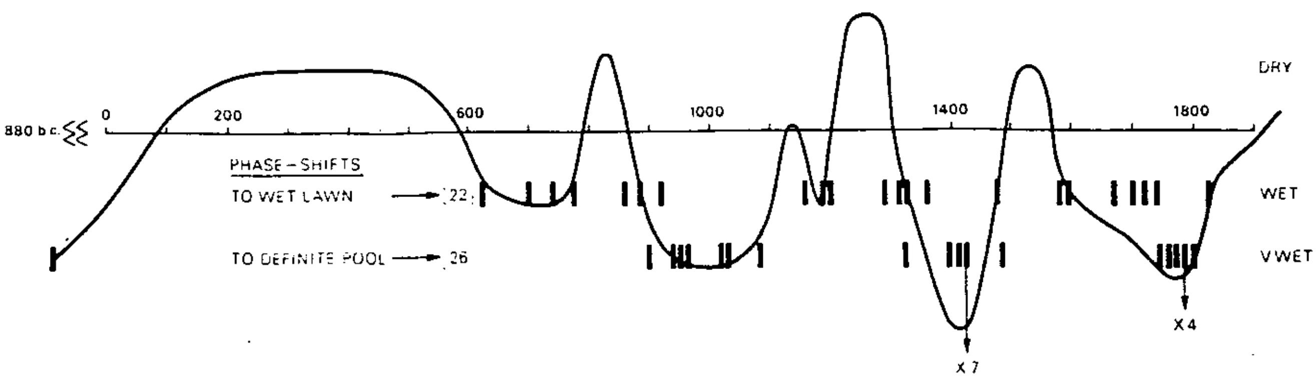


Fig. 7. Bolton Fell Moss, England. The degree of moisture of the peat-forming surface since AD 90 (Barber 1981), as based on various palaeobotanical information. The height of the 'dry' peaks is an indication of the extent, the dry nature of the vegetation and the state of weathering of the hummocks.

possible to discern distinct fluctuations in the degree of dampness of the peat-forming environment. There was no degradation of the peat due to drying out and oxidation as a result of climatic developments. In this respect, the results for the Netherlands fit in well with what has been found in Bolton Fell Moss, although the precipitation there, measured in periods of 10 years, is now 920 mm, 145 mm more than the present mean precipitation in the Netherlands.

There are no indications that the formation of peat in Bolton Fell Moss since the registration of meteorological data occurred differently from that in the preceding 2000 years; in other words, the conditions for raised-bog formation are still present there. It is also certain that in the Netherlands optimal conditions for raised-bog formation were present from c. 800 BC until well in the Middle Ages. There is no reason to assume that any climatic change leading to the cessation of raised-bog formation has taken place in the Netherlands since then, that would not be noticeable in the peat formation in England. Consequently we assume that in the Netherlands too the climatic conditions are still favourable for the formation of ombrogenous peat.

Prior to 2000 BC, desiccation events occurred in a number of raised bogs in the Netherlands which were evidently not the results of climatic drought in the form of very low precipitation and/or high temperatures. In the Bourtanger Moor east of Emmen, for example, around 2500 BC part of the raised-bog surface dried out as a result of substantial drainage by vertical discharge of bog water (Casparie 1972). In the Engbertsdijksveen a large area of raised bog became burnt away around 2100 BC as a result of the deep drainage of water into the sandy subsoil (van Geel & Dallmeijer 1986). After 2000 BC there were also instances of drying out of the raised-bog surfaces, although much more superficially or for shorter periods of time, in which the climatological component is discernible. Between c. 1200 and 700 BC there were somewhat greater fluctuations in precipitation and temperature. Around 850 BC the mean temperature decreased, probably by about 1°C. Very detailed research on the peat stratigraphy of the Bargerveen (Dupont 1985) shows a succession of somewhat wetter, sometimes very wet and somewhat drier phases, the overall result of which was increased dampness. This corresponds to peat-stratigraphic information from elsewhere (Casparie 1972; van Geel 1978). Thus around 1200 BC a few hectares of raised-bog surface of the southern part of the Bourtanger Moor dried out, while the contact zones remained wet: a consequence of decreased precipitation. Less than a century later the bog surface became considerably wetter, and subsequently – partly as a result of the marked expansion of the growth of the large-leaved *Sphagnum imbricatum* and *S. papillosum* – it apparently became somewhat less wet. Around 800 BC the mire became wetter again; the water supply on the bog surface increased, partly because of the temperature decrease. Around 500 BC extensive erosion occurred following a bog burst in the southern part of the Bourtanger Moor; the accelerated discharge of water did not result in drying out of the bog to any great depth. These conspicuous peat-stratigraphic phenomena between 1200 and 700 BC indicate that a new hydrological equilibrium had been reached in the formation of ombrogenous peat, under conditions of lower temperatures and slightly higher precipitation.

Between AD 1300 and 1400 *Sphagnum imbricatum* was substituted by *S. magellanicum* in the raised-bog surface of Bolton Fell Moss (Barber 1981). This phenomenon, which has been observed in many raised bogs, is ascribed to a very wet period (Fig. 5) after the 'little climatic optimum' (table 5). No data are available on the way in which this increasing precipitation affected raised-bog formation in the Netherlands. What we do know is that during the 'little optimum' fen-peat deposits became more readily accessible to man and could be reclaimed, and that after c. AD 1300 this peat became much wetter again, at least locally.

3.1.4. *Conclusions*

The raised bogs in the Netherlands (or their remaining relics) can be classified as plateau-type (or lens-type) raised bogs. A plateau-type raised bog is characterized by a slightly domed relief; the centre of the mire surface is almost flat. In its totality it is therefore a kind of weakly convex lens. Raised bogs of this type are situated in the Oceanic, the Suboceanic and the Subcontinental climate. The Netherlands lies in the transitional zone between the Oceanic and the Suboceanic climate types.

Peat-stratigraphic research in the Netherlands has shown that conditions were favourable for the formation of ombrogenous peat from c. 4000 BC until into the Middle Ages, at least in the northern Netherlands. It is evident that in this period there were distinct fluctuations in the degree of dampness of the peat-forming environment. There was no degradation of the peat as a result of drying out and oxidation caused by climatic developments.

On the basis of peat-stratigraphic information from surrounding countries (Great Britain and northwestern Germany) it can be deduced that since c. 4000 BC no climatic changes have occurred in the Netherlands which could have resulted in the cessation of the formation of raised bog. Climatic conditions for the formation of raised bog still prevail.

On the basis of the meteorological climate analysis according to Lamb it seems reasonable to assume that the Atlantic and the beginning of the Subatlantic were periods which were very favourable for the initial development of raised bogs, as optimal damp conditions (higher intensity of precipitation and somewhat lower temperatures) were then prevalent. The first half of the Atlantic, the Subboreal and also the remaining part of the Subatlantic can be regarded as having been moderately favourable to favourable for the initial development of raised bogs (conditions then being somewhat less damp).

A minimum precipitation of c. 700 mm per year and a mean July temperature of 16–17°C or less (mean annual temperature c. 9°C) are important conditions for the formation of plateau-type raised bog. This conclusion can be based on our knowledge of the extent and types of ombrotrophic peat in Europe in relation to climate, on the climatic developments in relation to raised-bog growth, on studies of the water balance in bogs from western to eastern Europe and in particular on the Dutch situation, and the former distribution of raised bogs in the Netherlands.

The mean precipitation surplus for the (lens-type) raised bogs in the Netherlands is 150–275 mm per year.

3.2. Stratigraphy and palaeo-ecology of peat deposits in the Bourtanger Moor

3.2.1. *Introduction*

3.2.1.1. *General points*

This section of chapter 3 deals with the mire development in the Bourtanger Moor in the northeastern Netherlands (Fig. 8). A part (about 35 km^2) of this former raised bog has been studied in detail with regard to its peat stratigraphy, and the peat-forming mechanisms involved in its development have been described (Casparie 1972, 1980, 1984a). The first peat deposits here date from the end of the Weichselian Glacial, c. 11,000 BC. The growth of peat here came to a standstill in the 18th and 19th century AD as a result of drainage for the purpose of facilitating peat digging.

Detailed studies of the peat stratigraphy and palaeobotany of this and adjacent mire areas have greatly added to our understanding of the development of peat deposits and have provided further insight into the processes controlling peat formation (Dupont 1985; Van Geel 1978; van Geel & Dallmeyer 1986; Van der Straaten 1981; Teunissen 1975). The extensive research on macroscopic plant remains of peat deposits by

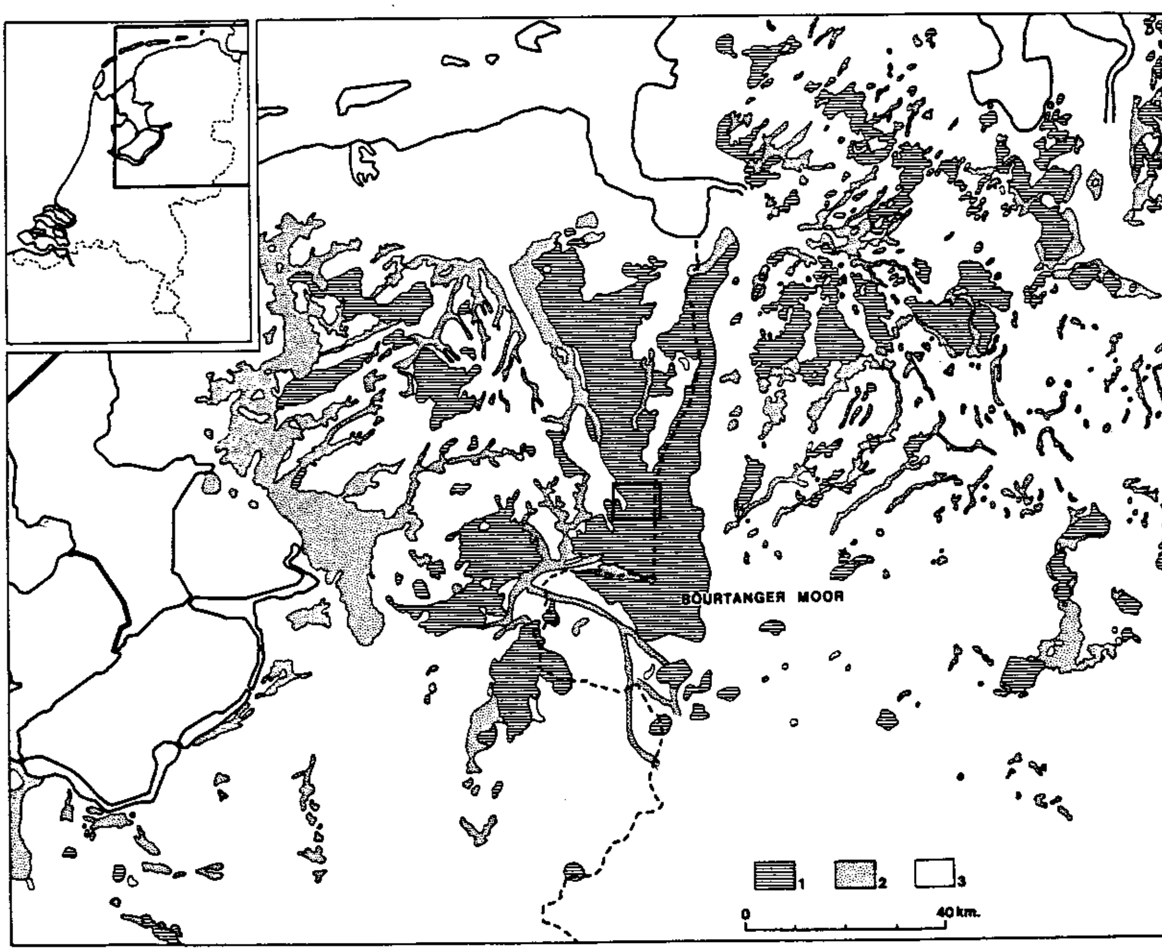


Fig. 8. Bourtanger Moor in the northeastern Netherlands, part of Fig. 4. The study area is indicated with a rectangle. 1. raised bog; 2. fen peat; 3. other soils (sand, clay, boulder-clay).

Grosse-Brauckmann (1964, 1972, 1974, 1975, 1979, 1980, 1985, 1986) has greatly increased our knowledge of subfossil peat-forming plant communities. The hydrology of mire systems is receiving increasing attention, also where subfossil peat deposits are concerned (Eggelsmann 1980; Ingram 1983; Streefkerk & Oosterlee 1984; Streefkerk & Casparie 1987).

The aim of the research described here was to provide insight into the development of vegetation and soil in the Bourtanger Moor since the end of the Weichselian period, by means of describing the various peat layers and studying the subfossil macroscopic remains contained in them. Much attention has been devoted to conclusions on the environmental conditions (climate, hydrology) in the different periods, based on the texture of the peat, the degree to which the peat layers have decomposed (humified) and the composition of the macroscopic remains, pollen and spores. The archeological aspect of the research, concerning the possibilities for use of the area by man in prehistoric times (Casparie 1982, 1984b, 1986b), is not dealt with here.

3.2.1.2. *Research methods*

The field research was carried out between 1959 and 1968 in an area where peat digging had been practised intensively for several decades already; at the time this work was still in full progress. Many vertical peat-faces were present, often exceeding 1 km in length. Almost all of the peat-faces, with a total length of more than 100 km, were surveyed. A more detailed study was made of almost 10 km of peat-faces, involving levelling, measuring and drawing (Casparie 1972). Together they form a number of cross-sections through the mire area.

At a number of sites, parts of peat-faces were studied more closely and subsequently drawn in detail with the aid of a frame with a grid of 10 x 10 cm. The fieldwork also involved making geological maps, corings in the mineral subsoil and measuring stumps. Excavations of prehistoric wooden trackways also formed part of the field research. Many samples of monoliths, peat blocks, wood remains and mire minerals were collected, for various analyses in the laboratory. In addition interviews were held with many local inhabitants, in particular peat diggers.

The laboratory research involves pollen analysis, rhizopod analysis, the investigation of macroscopic remains, identification of mosses, dendrochronology, ^{14}C-datings, and the analysis of characteristic features of growth of bog trees.

The peat in the study area was found in a rather strongly shrunken state as a result of the intensive drainage for the purpose of facilitating peat digging. The thickness of the peat layers mentioned in the discussion concern the dried-out situation, often less than half of the original thickness.

On the basis of the data of this mire research it is possible to give a synthesis of the peat growth in the study area between c. 11,000 BC and the beginning of the Christian Era. This synthesis is presented here in the form of ten cross-sections of the peat stratigraphy in chronological order (Fig. 11). Six palaeogeographic maps (Fig. 12) show the horizontal distributions of the deposits. In the cross-sections the original thickness of the peat deposits is given which has been reconstructed on the basis of a large data set. The data concerned and the argumentation involved are not discussed in any further detail. These cross-sections and the maps are rather strongly schematized. The original thickness of the total peat deposits was about 10 m. Since the drainage of the bog after the 17th century and as a result of buckwheat cultivation on the drained mire surface since the end of the 19th century, the remaining complex of peat deposits measures 3–4 m in thickness.

The research concerned subfossil plant remains. Nomenclature follows Van der Meyden et al. (1983) for phanerograms and Margadant & During (1982) for mosses.

3.2.1.3. *Outline of the description of the mire development*

The peat development is generally described chronologically, starting with the oldest layers and ending with the youngest; broadly speaking these are the lowermost and uppermost layers, respectively, of the peat deposits. Sometimes it is necessary to deviate slightly from this for the sake of overall clarity.

First of all, attention will be focused on the geological situation of the Bourtanger Moor; secondly the Late Glacial peat deposits are discussed. This covers the development up until 8300 BC. Then the Holocene fen peat formations are described. Subsequently attention is devoted to the gyttja complex, that is also included among the fen peat deposits. This topogenous mire development of the study area can be roughly dated to between 8300 and 4100 BC.

An outline is then presented of the seepage peat in this area. Soligenous peat formation, which can be dated here to between 5200 and 3100 BC, occurs in various places. Regional seepage is of great influence on the peat development in large parts of the Bourtanger Moor, partly because watersheds are broken through, as it were.

Finally, the formation of ombrogenous peat is discussed. Here we are concerned with two extensive raised-bog complexes with deposits of highly humified *Sphagnum* peat, a deposit of *Menyanthes-Betula* peat, the deposits with the development from highly humified to poorly humified *Sphagnum* peat, and the peat deposits in the western bog margin, where the influence of the higher mineral soils on the peat formation is noticeable. In the discussion of the formation of ombrogenous peat, that dates from 4500 BC onwards, the emphasis lies on the development of the types of peat distinguished in relation to the hydrology. Therefore attention is focused on the ombrogenous water supply, and on the spatial structures of the formation of raised bog, notably the hummock-hollow systems, prior to the discussion of the peat deposits. The discussion on the ombrogenous peat deposits ends with some considerations about the specific hydrological dynamics of the raised bog ecosystem, with special reference to the 'system-linked water discharge' (Dutch: 'systeemgebonden waterafvoer').

3.2.2. *The mineral subsoil and Late Glacial deposits (up until 8300 BC)*

3.2.2.1. *The geological situation*

The ice-marginal valley in which later the Bourtanger Moor develops (Fig. 9) comes into being during the last expansion of the ice sheet of the Saalian Glacial (Ter Wee 1962). The valley is oriented southeast-northwest, and is 70–80 km long and 12–15 km wide. It has a steep western slope, formed by the Hondsrug. This is the eastern erosion margin of the Drenthe Plateau, the boulder-clay plateau formed during an earlier phase of the Saalian. Towards the end of the Weichselian Glacial (table 1) the valley has a depth of 10–20 m (Fig. 10).

The subsoil consists of fluviatile sands, covered with a layer of fluvial loam (Fig. 11A, deposits 1 and 2). Still during the Weichselian, the small river known as the Hunze originates in the western part of the valley, more or less at the foot of the Hondsrug. This river cuts out a valley about 1 m deep and 2–3 km wide with an asymmetric relief (Fig. 11). The Hunze valley has only a very slight gradient of c. 0.4 promille. In this valley there are a few coversand ridges, situated transversely with respect to the direction of the river flow, which do not completely cut off the valley, but nevertheless have a great influence on the drainage. Such a coversand ridge is present in the study area, namely the Postwegrug (Postweg ridge, Fig. 10).

In the ice-marginal valley there are also low, fluviatile ridges, situated in the longitudinal direction of the valley. They vary in width from a few hundreds of metres to about 1 km, and in height from 1 to 3 m. Some of these ridges have a layer of fluviatile loam on top. The ridges originate in the course of the Weichselian. In a number of cases they form the rather gradual eastern slope of the Hunze valley. A fluviatile ridge is present in the study area, namely the Berkenroderug.

The study area is situated just north of the Postwegrug, about 12 km north of the starting point of the Hunze (Fig. 10). The drainage of the area south of the Postwegrug, that extends over c. 45 km^2 and that can be called the upper course of the Hunze, is concentrated towards a low spot, almost 200 m wide, in the coversand ridge. This low-lying spot is called the spillway. The Berkenroderug (Berkenrode ridge, Fig. 10), that initially forms the eastern border of the peat deposits, becomes overgrown at a later stage.

The supply of water from the upper course of the Hunze via the spillway in the Postwegrug, determines to a great extent the formation of peat in the study area. This upper course cannot be regarded as a true river or stream with flowing water. It consists rather of a gulley-shaped depression with an unsettled relief in the subsoil, that slows down the drainage to a considerable degree as a result of the very slight gradient. As a consequence, sufficient water logging occurs for the formation of peat. This is already the case in the Late Glacial (Table 1), c. 11,000 BC, when as a result of a (slight) amelioration in the climate the permafrost in the valley thaws at the surface, and the water thus produced cannot soak away into the subsoil. It seeks its way downstream over the surface. From the spillway onwards, towards the north, situations thus arise that are favourable for the formation of mire: a waterlogged soil with extensive pools present here and there.

3.2.2.2. *Late Glacial Deposits* (*c.* 11,000–8,300 *BC*)

The first organic formation is a Hypnaceae peat

Table 6. Botanical composition of the Late Glacial deposits, based on the macroscopic remains: seeds, fruits and leaves.

	Hypnaceae peat	Loess peat	*Betula* wood peat layer
Calliergon sarmentosum	+++		
Scorpidium scorpioides	+		
Drepanocladus indet.	++		
Potentilla palustris	+		
Typha latifolia	+	+++	++
Menyanthes trifoliata	++		+
Equisetum	+++		+
Triglochin	+		
Dryopteris	+	++	++
Sparganium-type	+		
Myriophyllum	+		
Potamogeton	+	+	
Gramineae (incl. *Phragmites*)	++	+	+
Cyperaceae	+++	+	+
Carex cf. *paniculata*	+		
Carex cf. *trinervis*	++		
Carex indet.	+	+	
cf. *Scirpus fluitans*	++		
cf. *Puccinellia*	+		
Potentilla anserina	+	+	++
Juncus cf. *conglomeratus*		++	
Juncus cf. *effusus*		+	
Sphagnum		+	++
Pediastrum		++	
Filipendula		+	+
Betula			++

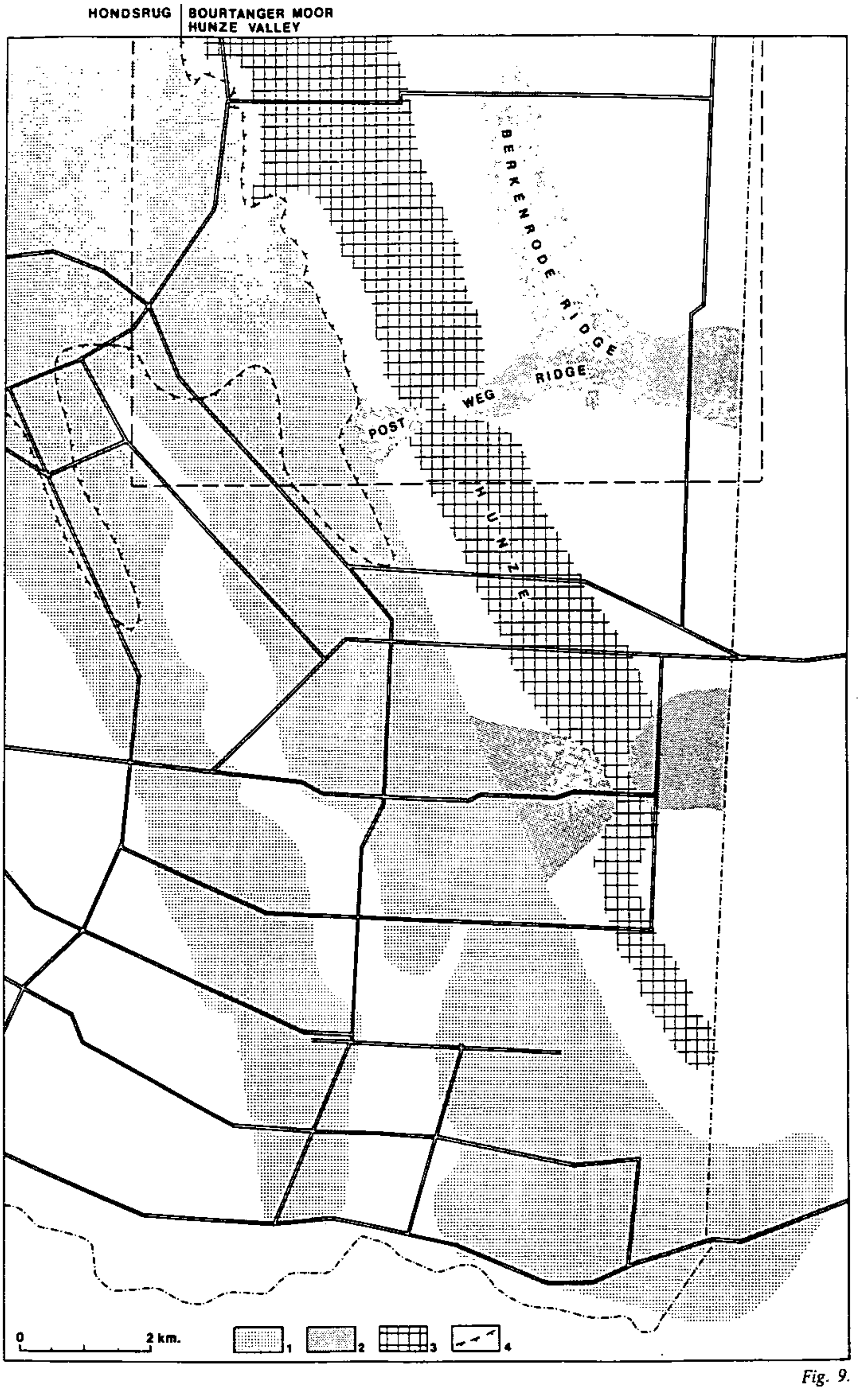

HONDSRUG
BOURTANGER MOOR
HUNZE VALLEY
BERKENRODE RIDGE
POST WEG RIDGE
HUNZE
0
2 km.
1
2
3
4

Fig. 9.

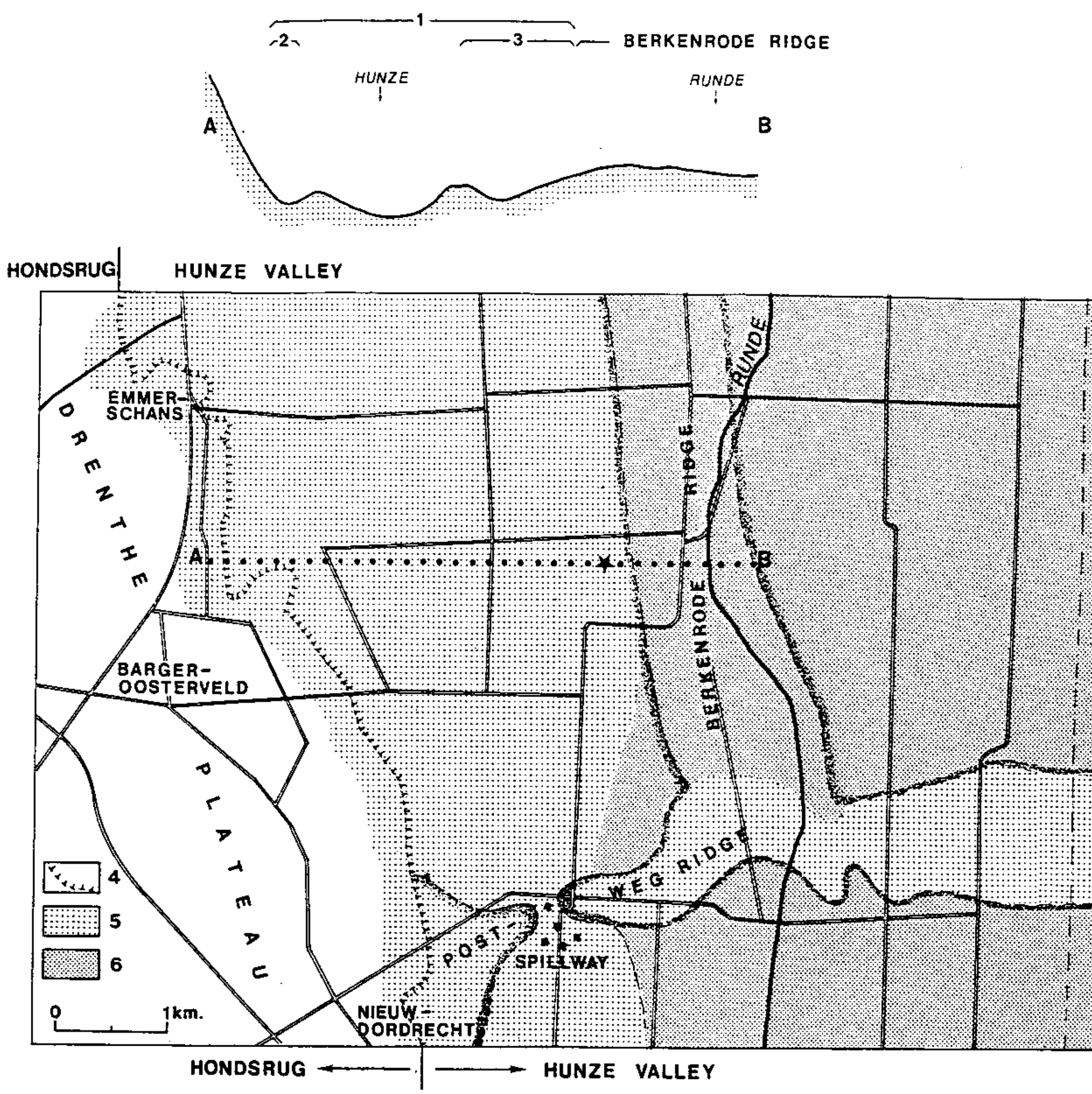
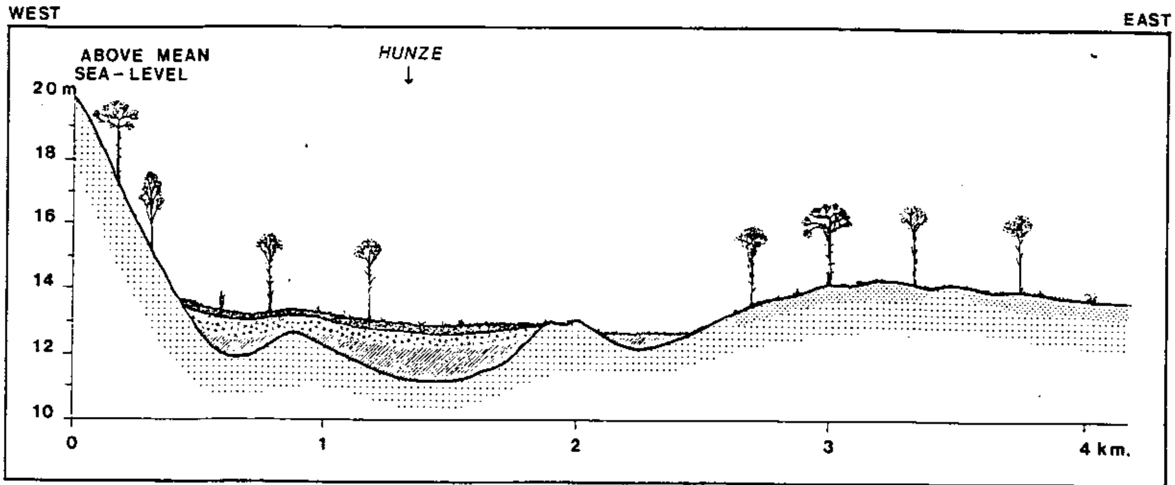
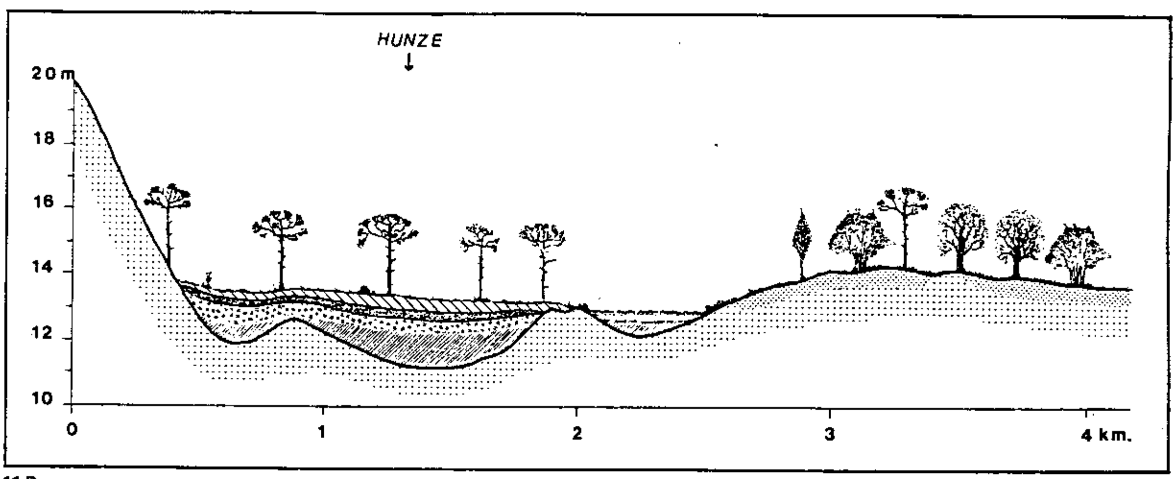


Fig. 10. Study area with indication of the Berkenrode ridge and the Postweg ridge with the spillway, with the last course of the bog stream Runde (19th century AD) and with the villages Emmerschans, Bargeroosterveld and Nieuw-Dordrecht, indicating the western margin of the raised bog. A....B: situation of the cross-sections of Fig. 11. The location of the peat section shown in Fig. 1 is indicated with an asterisk. At the top of the Figure the cross-section through the Hunze valley as used for Fig. 11 is shown. 1. Hunze valley; 2. steep western slope of the Hunze valley; 3. gradual eastern slope of the Hunze; 4. western bog margin; 5. fluviatile sand below the peat deposits; 6. fluvial loam below the peat deposits.

Fig. 9. Southernmost part of the ice-marginal valley in which the Bourtanger Moor develops, with the upper course of the rivulet Hunze, modified after Ter Wee (1962), Streefkerk & Oosterlee (1984), and Casparie (1984). 1. boulder-clay (Drenthe Plateau); 2. sand ridges in the Hunze valley influencing the peat growth; 3. course of the Hunze, direction of discharge SE to NW; 4. bog margin. The rectangular study area is indicated by dashed lines near the top of the map. The location of the study area is also shown in Fig. 8. It forms the base of the maps of figs. 10 and 12. In these maps some of the present-day roads and the Dutch-German border are indicated.



11 A 8500 -8300 BC



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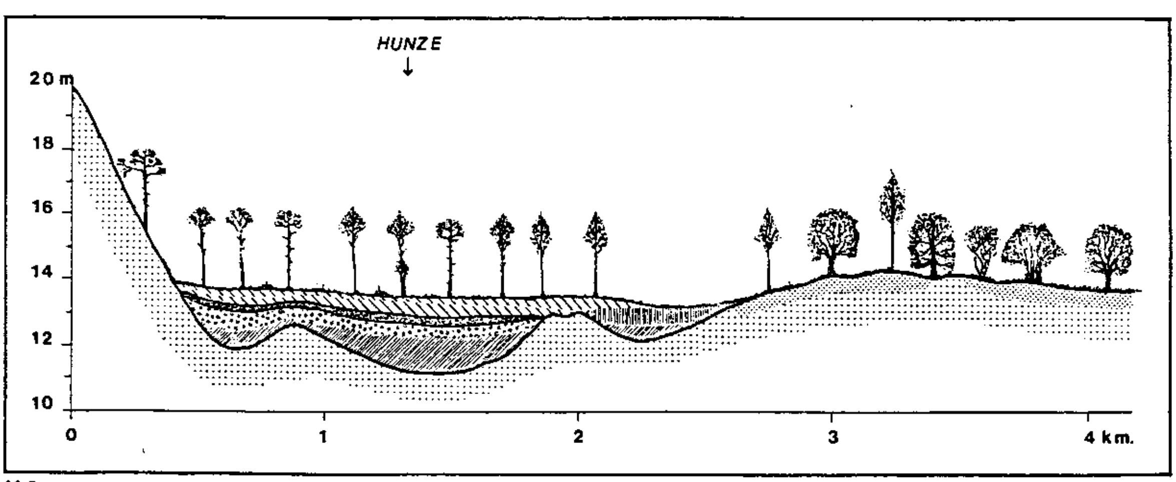
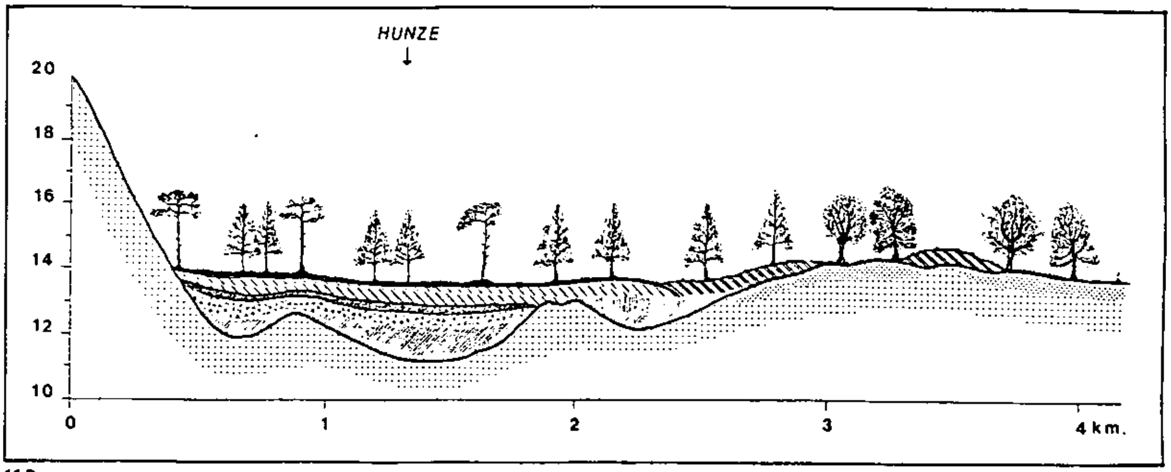
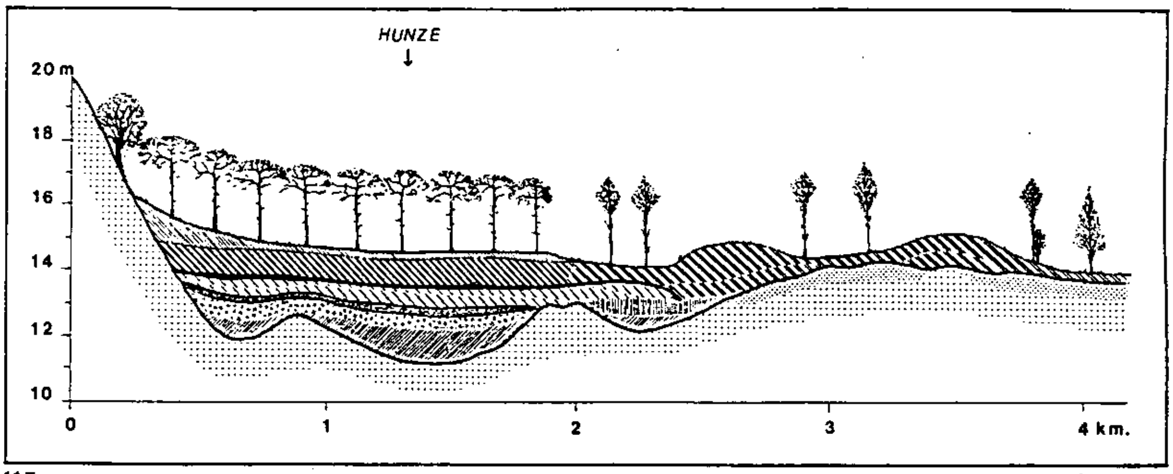


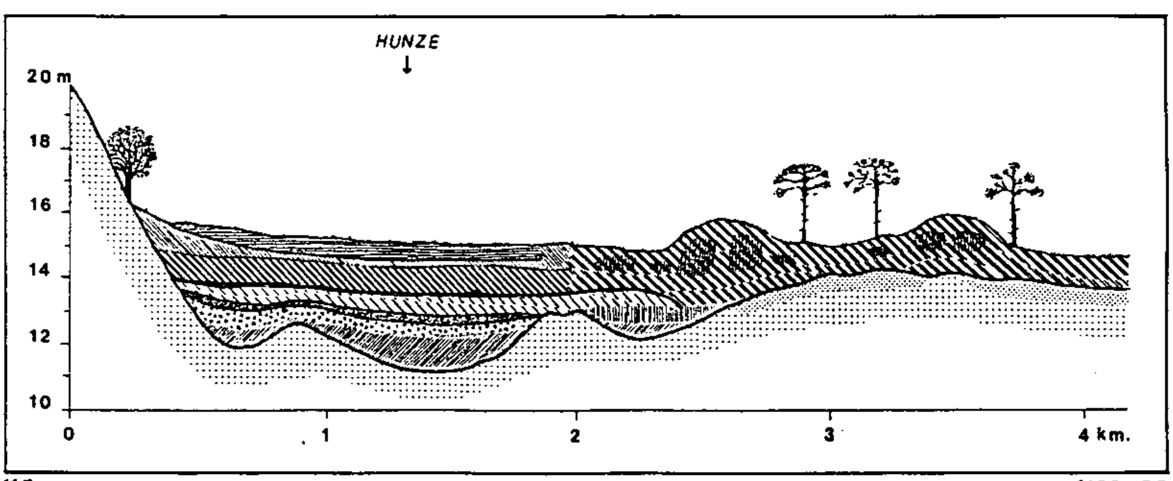
11 C 6000 BC



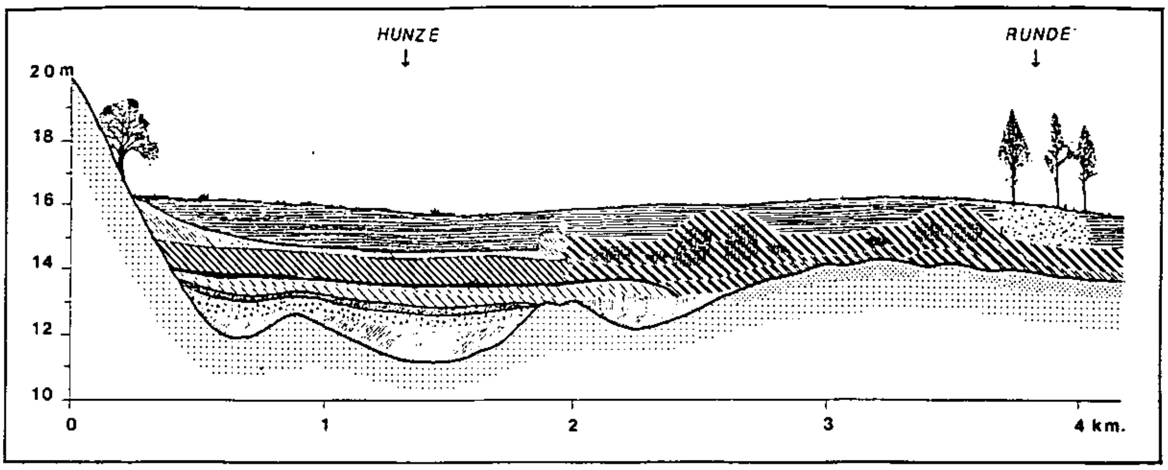
11D 5000 BC



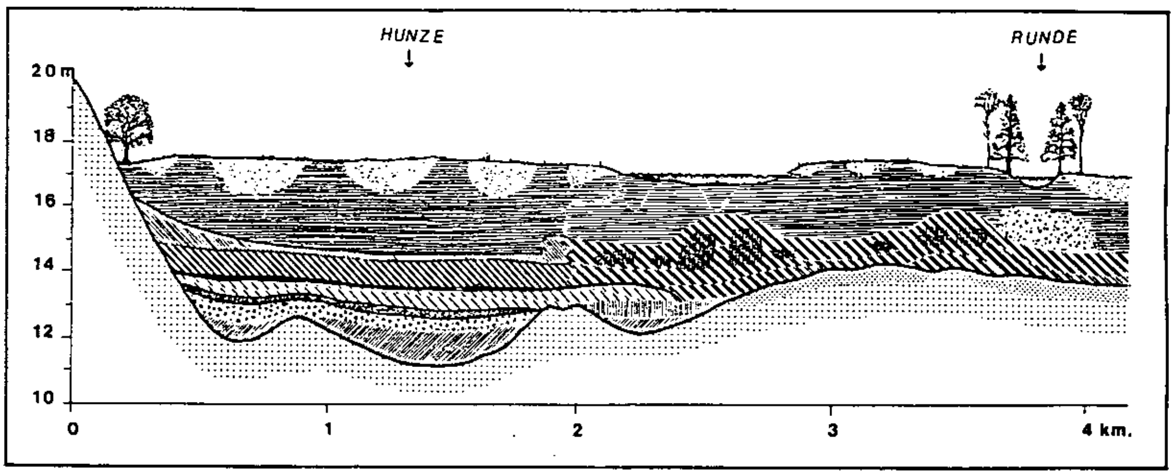
11E 4500 BC



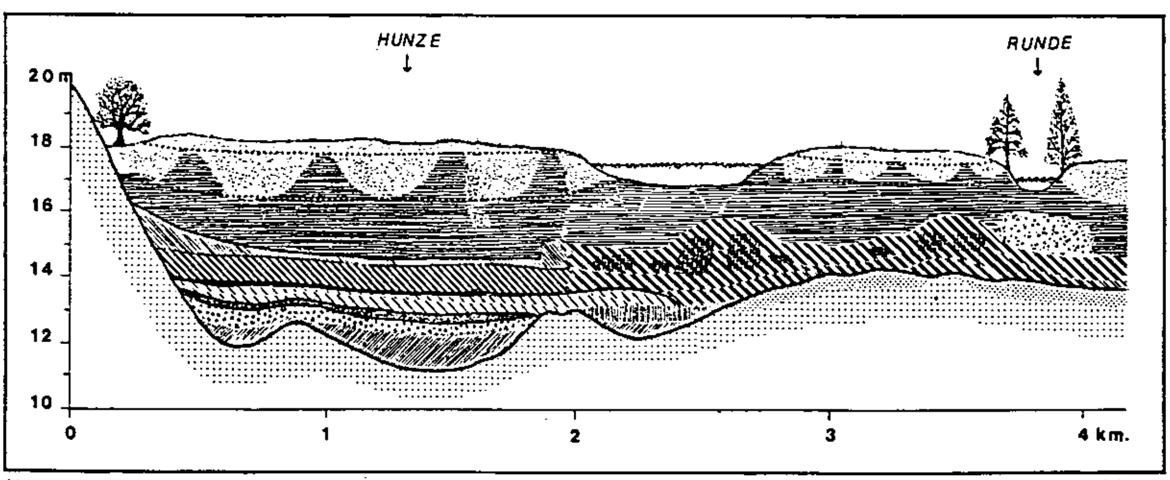
11F 3100 BC



11G 2000 BC



11H 1000 BC



11 I 500 BC

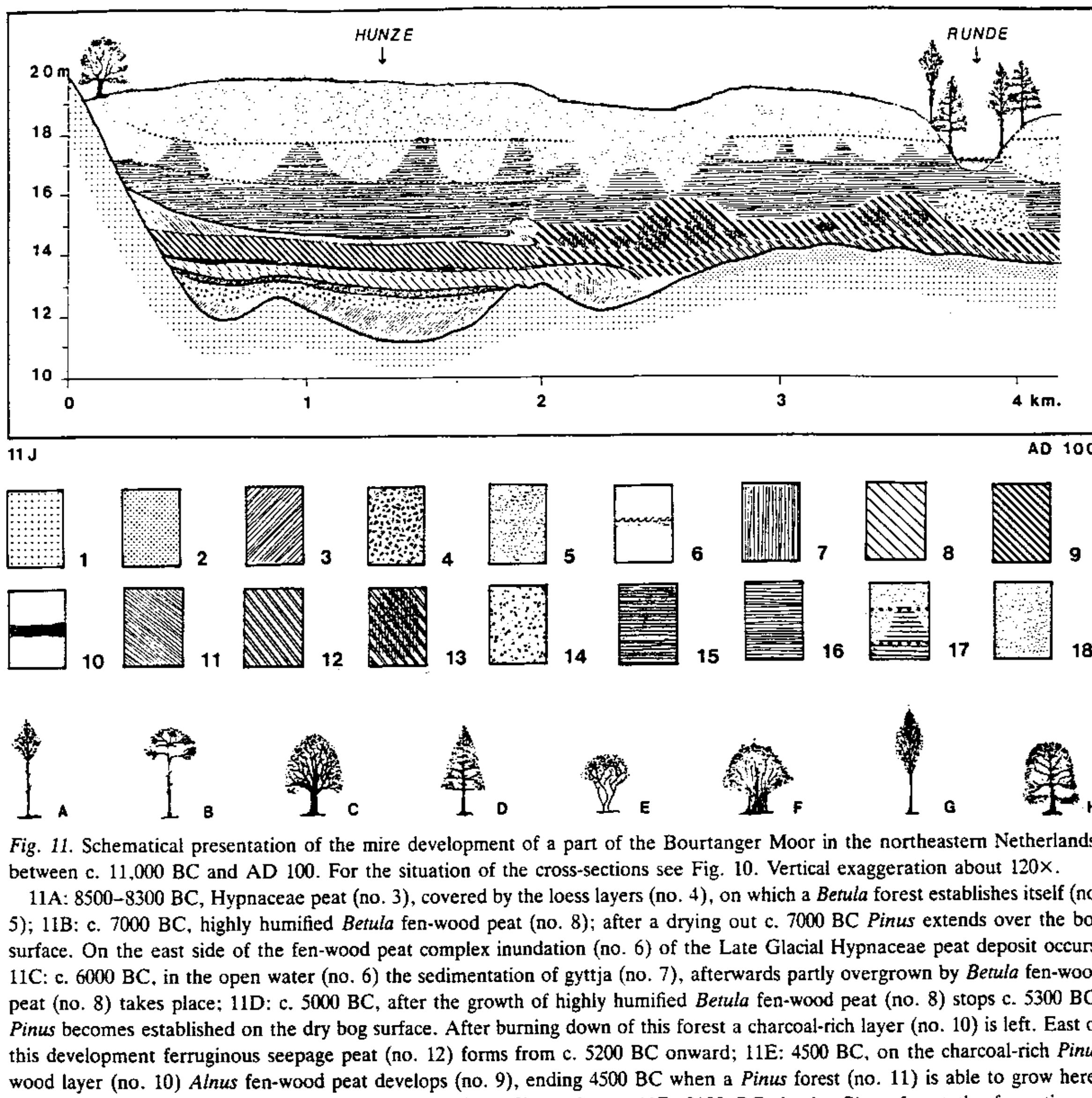


Fig. 11. Schematical presentation of the mire development of a part of the Bourtanger Moor in the northeastern Netherlands, between c. 11,000 BC and AD 100. For the situation of the cross-sections see Fig. 10. Vertical exaggeration about 120×.

11A: 8500–8300 BC, Hypnaceae peat (no. 3), covered by the loess layers (no. 4), on which a *Betula* forest establishes itself (no. 5); 11B: c. 7000 BC, highly humified *Betula* fen-wood peat (no. 8); after a drying out c. 7000 BC *Pinus* extends over the bog surface. On the east side of the fen-wood peat complex inundation (no. 6) of the Late Glacial Hypnaceae peat deposit occurs; 11C: c. 6000 BC, in the open water (no. 6) the sedimentation of gyttja (no. 7), afterwards partly overgrown by *Betula* fen-wood peat (no. 8) takes place; 11D: c. 5000 BC, after the growth of highly humified *Betula* fen-wood peat (no. 8) stops c. 5300 BC, *Pinus* becomes established on the dry bog surface. After burning down of this forest a charcoal-rich layer (no. 10) is left. East of this development ferruginous seepage peat (no. 12) forms from c. 5200 BC onward; 11E: 4500 BC, on the charcoal-rich *Pinus* wood layer (no. 10) *Alnus* fen-wood peat develops (no. 9), ending 4500 BC when a *Pinus* forest (no. 11) is able to grow here. East of this the ferruginous seepage peat growth (no. 12) continues; 11F: 3100 BC, in the *Pinus* forest the formation of brown-black highly humified *Sphagnum* peat (no. 15) starts shortly after 4500 BC. In the ferruginous seepage peat deposits (no. 12) the formation of siderite (no. 13) occurs from c. 4500 BC onward, until the seepage stops 3100 BC. Locally *Pinus* starts to grow on the desiccated seepage peat surface; 11G: 2000 BC, the deposition of brown-black highly humified *Sphagnum* peat (no. 16) continues in the hummocks. On the ferruginous seepage peat surface blue-black highly humified *Sphagnum* peat (no. 16) is forming and east of this complex the growth of *Menyanthes-Betula* peat (no. 14) occurs. In this area the bog river Hunze develops gradually; 11H: 1000 BC, on the brown-black highly humified peat (no. 15), on the blue-black highly humified peat (no. 16) and on the *Menyanthes-Betula* peat (no. 14), hummock and hollow systems develop, with highly humified hummock peat and poorly humified hollow peat (no. 17). In contact zones between the domed complexes accumulations of water (no. 6) develop; 11I: 500 BC, shortly before the bog burst. In parts of the domed complexes the deposition of poorly humified *Sphagnum* peat (no. 18) starts to dominate in the hummock-hollow systems. The bog lake in the contact zone is completely filled with water; 11J: AD 100, after the bog burst, on the entire bog surface the accumulation of fresh to poorly humified *Sphagnum* peat predominates, except for the south-north contact zone in which the bog river Runde has its course. Here the formation of fen-wood peat, not fed by groundwater but by the superficial discharge, takes place.

Key to the cross-sections of Fig. 11A-J: 1. sand; 2. fluvial loam; 3. Hypnaceae peat (German: 'Braunmoostorf') (c. 11,000–9500 BC); 4. loess layer (c. 9500–8700 BC); 5. *Betula* wood peat layer (c. 8700 BC); 6. open water; 7. gyttja deposit (c. 6800–5300

(German: 'Braunmoostorf') that can be dated to between c. 11,000 and 9500 BC. Subsequently, between 9500 and 8700 BC, a thin loess layer is deposited, and then a thin layer of wood peat, in which *Betula* predominates. This layer can be dated to between 8700 and 8300 BC. Table 6 provides details of the botanical composition of these deposits. Fig. 11A shows a cross-section of the stratigraphy of the fen peat deposits, c. 8300 BC.

Hypnaceae peat. This orange peat that rapidly oxidizes upon exposure to the air into a blue-black colour forms a deposit 10–50 cm thick, which is not layered, but follows the subsoil relief closely over a width of 2–3 km, from the spillway onwards in a northwesterly direction (Fig. 11A, deposit 3; Fig. 12.1). The fen mire with such species as *Calliergon sarmentosum*, *Scorpidium scorpioides*, *Drepanocladus* and various aquatic plants (table 6) must have been very wet. In the pools brown gyttja is deposited. Around the fringes of these pools *Phragmites* becomes established extensively.

The beginning of this peat formation falls in the Older Dryas (Table 1), notably in the warmer Bølling interstadial. The amelioration in climate in this period ultimately leads to the disappearance of the permafrost, approximately in the middle of the relatively warm Allerød phase. The resulting considerably deeper drainage that is thus brought about signifies the end of the formation of Hypnaceae peat, without the environment becoming really dry. The peat formation is thus dated to between 11,000 and 9500 BC.

Loess layer. The western part of the Hypnaceae peat complex is covered with a layer of grey eolian loam, containing charcoal at the top (Fig. 11A, deposit 4; Fig. 12.1). On the west side this loess layer is about 20 cm thick; it wedges out towards the east over a distance of about 2.3 km. The deposit has more or less the shape of a semicircle with the midpoint right over on the west side. The layer has been deformed to some extent as a result of cryoturbation. The material originates from the higher Drenthe Plateau on the west side.

The deposition of loess coincides with the expansion of *Pinus* on the Drenthe Plateau in the Allerød phase, and continues until during the beginning of the Younger Dryas. This deposition of predominantly mineral material can therefore be dated to between c. 9500 and 8700 BC. The concentration of charcoal marks the transition from Allerød to Younger Dryas, c. 8900 BC.

The loess is deposited on top of the very wet Hypnaceae vegetation (including *Pediastrum*, Table 6). The great expansion of *Typha latifolia* indicates that the environment becomes richer, undoubtedly as a result of the abundance of minerals in the deposit. The loess deposit (of the Younger Coversand B) and the expansion of *Pinus* on the higher soils, after the middle of the Allerød phase, are both probably associated with the fact that the soil of the Drenthe Plateau becomes drier as a result of the disappearance of the permafrost. The charcoal deposition at the end of the Allerød is connected with extensive forest fires on the uplands. These may have been caused by man. It is also possible that the sudden occurrence of a cold period marking the transition from Allerød to Younger Dryas, results in

BC); 8. *Betula* fen-wood peat (8300–5300 BC); 9. *Alnus* fen-wood peat (c. 5000–4500 BC); 10. charcoal-rich *Pinus* wood layer (5300–4900 BC); 11. *Pinus* transitional peat (pine stumps) (4500–4100 BC); 12. ferruginous seepage peat (5200–3100 BC); 13. concentrations of siderite lenses (bog iron-ore) (c. 4500–3100 BC); 14. *Menyanthes-Betula* peat (3100–1900 BC); 15. brown-black highly humified *Sphagnum* peat (4500–2000 BC); 16. blue-black highly humified *Sphagnum* peat (3100–1500 BC); 17. transition from highly to poorly humified *Sphagnum* peat (2000–c. 500 BC); 18. poorly humified *Sphagnum* peat (from c. 500 BC on).
Trees: A. *Betula* sp.; B. *Pinus sylvestris*; C. *Quercus* sp.; D. *Alnus glutinosa*; E. *Fraxinus excelsior*; F. *Corylus avellana*; G. *Ulmus* sp.; H. *Tilia* sp.

the large-scale death of pine trees, thus facilitating forest fires (Casparie & Ter Wee 1981).

Considering that the total period during which the loess particles are airborne lasts about 700 years, there is a very low rate of deposition of the mineral material on the Hypnaceae peat-forming vegetation. Probably the period of eolian activity is relatively short, for example a few decades. It is unlikely that the formation of Hypnaceae peat comes to an end as a result of this deposition, as the growth of this peat stagnates also outside the area of bog influenced by the loess.

Betula wood peat layer. On top of the loess layer in many places a 5–8 cm thick peat layer is present mainly consisting of thin roundwood of *Betula* on which the bark is still present (Fig. 11A, deposit 5; Fig. 12.1). The material is not highly humified (as is the case with the later fen peat), nor is it greatly compacted. Locally the layer is absent, presumably as a result of erosion. The layer does not follow the distortions in the loess layer due to cryoturbation. It can therefore be dated to after 8700 BC, while the process of its formation comes to an end before 8300 BC. The total period during which this layer is forming is therefore relatively short.

The data are indicative of the development of an incipient birch forest on very wet soil; the presence of *Sphagnum* (Table 6) in this forest indicates oligotrophic environmental conditions. This suggests that here there is no supply of water from the area of the upper course of the Hunze, but that the availability of water can be related to waterlogged situations at the surface precisely before the definitive disappearance of the permafrost in this locality.

3.2.3. *Fen peat* (8300–3100 *BC*)

3.2.3.1. *Introduction*

This section deals with four peat deposits, that have been formed in a groundwater environment (topogenous and soligenous). The four deposits that can be distinguished are: a *Betula* carr (fen-wood) peat deposit (8300–5300 BC) covered by a *Pinus* wood peat layer (5300–4900 BC); an *Alnus* carr (fen-wood) peat deposit (5000–4500 BC) also covered by a *Pinus* wood peat layer (4500–4100 BC); gyttja deposits around this fen peat (6800–5300 BC), and a seepage peat complex (5200–3100 BC) to the east of the fen peat formations.

From c. 8300 until 4500 BC the upper course of the Hunze provides the water for this topogenous fen peat formation. During this period of almost 4000 years the water Table rises c. 2 m. There are a few interruptions in this water supply as a result of which the peat dries out to a considerable extent, for example c. 7000 BC and 5300 BC. When this happens the spillway in the Postrugweg dries up. As a result of the latter instance of drying out, extensive seepage of ferruginous water occurs in the study area. From that time on there are two different hydrological systems in the area, each with its own type of peat formation. The iron-poor topogenous system is supplied with water by the upper course of the Hunze; the iron-rich soligenous system involves regional seepage, with water supplied from the Drenthe Plateau. Fig. 11B-F shows cross-sections through the peat stratigraphy developed between 8300 and 3100 BC. For the spread of the deposits, see Fig. 12.2–4.

3.2.3.2. *Betula fen-wood peat and Pinus wood peat* (8300–4900 *BC*)

In the damp to wet environment that forms in the Hunze valley as a result of the recovery of the water supply after 8300 BC, *Betula* forests develop that produce a highly humified fen peat, with numerous thin layers of fragments of white bark (Fig. 11B, deposit 8; Fig. 12.2). This peat formation occurs in the entire region with Late Glacial deposits. The thickness of the complex is not known with certainty because the peat has been burnt. The thickness may have been 50–60 cm.

The plant species present in this forest include

Humulus and *Dryopteris*. *Filipendula*, *Phragmites*, *Menyanthes*, *Potamogeton* and also Cyperaceae indicate the presence of wet spots the extent and situation of which cannot be determined any more precisely. Initially *Sphagnum* as well as *Urtica* occur that may indicate a difficult incipient phase of the peat formation. The disappearance of various plant species indicative of damp conditions and the establishment of a dense *Pinus* forest point to a period of drying out around 7000 BC.

The *Pinus* forest must have been burnt down, at which time c. 40 cm of the peat that had formed until then burnt away too. The charcoal remains of this catastrophe are in evidence in only a few places. In this instance of drying out the peat-forming level does not reach the threshold level of the spillway in the Postrugweg. The drying-out process almost certainly originates as a result of a fall in the water level south of this spillway, leading to a standstill in the supply of water to the study area.

The duration of the pine forest is unknown. Nor is it known whether the formation of fen peat starts again immediately after the drying out. A hiatus cannot be excluded. After the fall in the water level in the area providing the water supply it is evident that a renewed supply of water over the threshold became available, resulting once again in the formation of *Betula* fen-wood peat. In the whole area in which this peat formed before c. 7000 BC, once again birch carr with many wet spots develops, considering the occurrence of *Phragmites*, *Menyanthes* and *Potamogeton*. In the western periphery of this forest the plant species occurring include *Rubus*

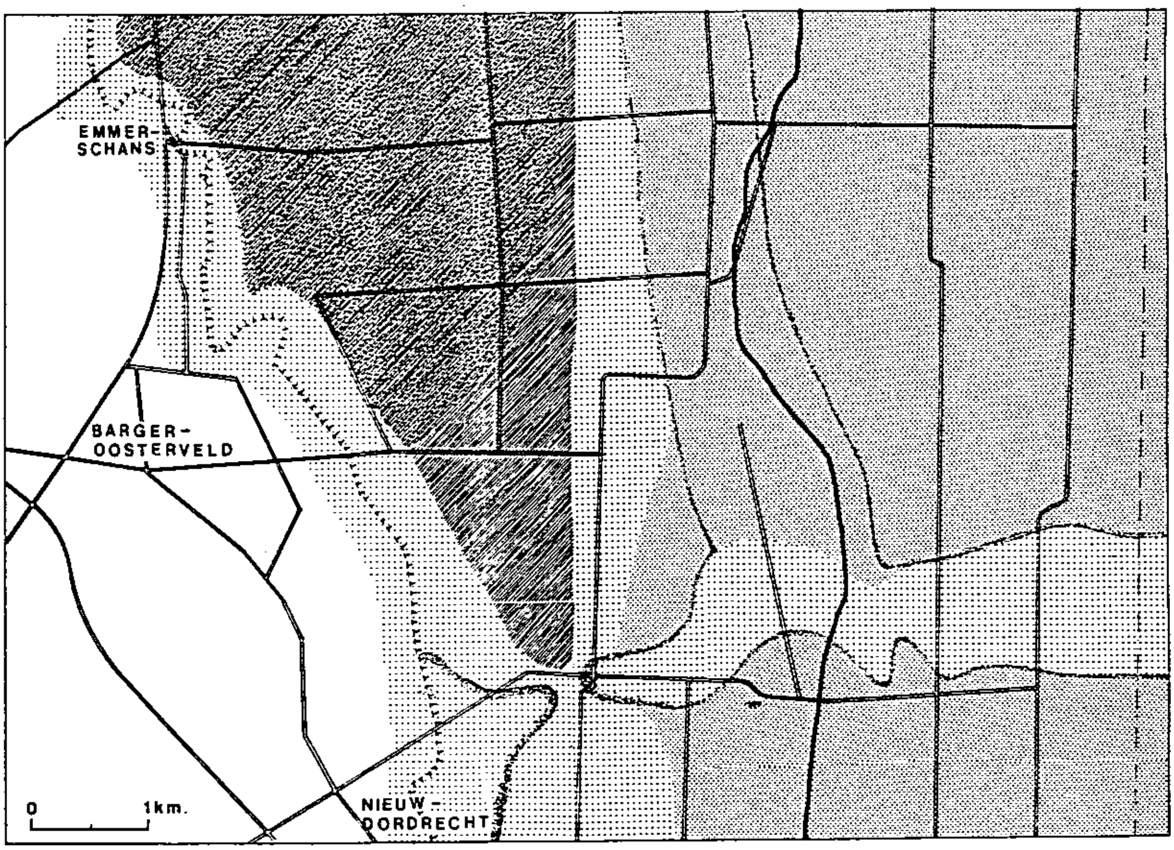


Fig. 12.1

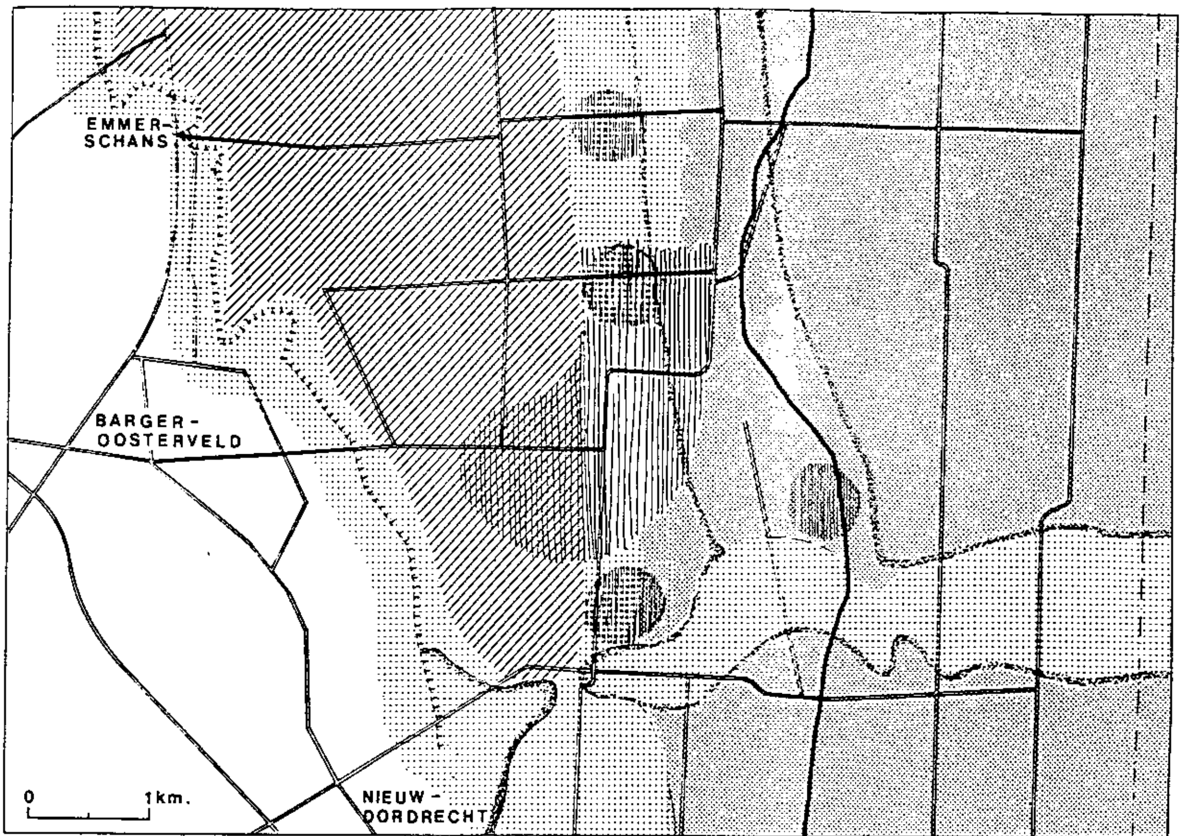


Fig. 12.2

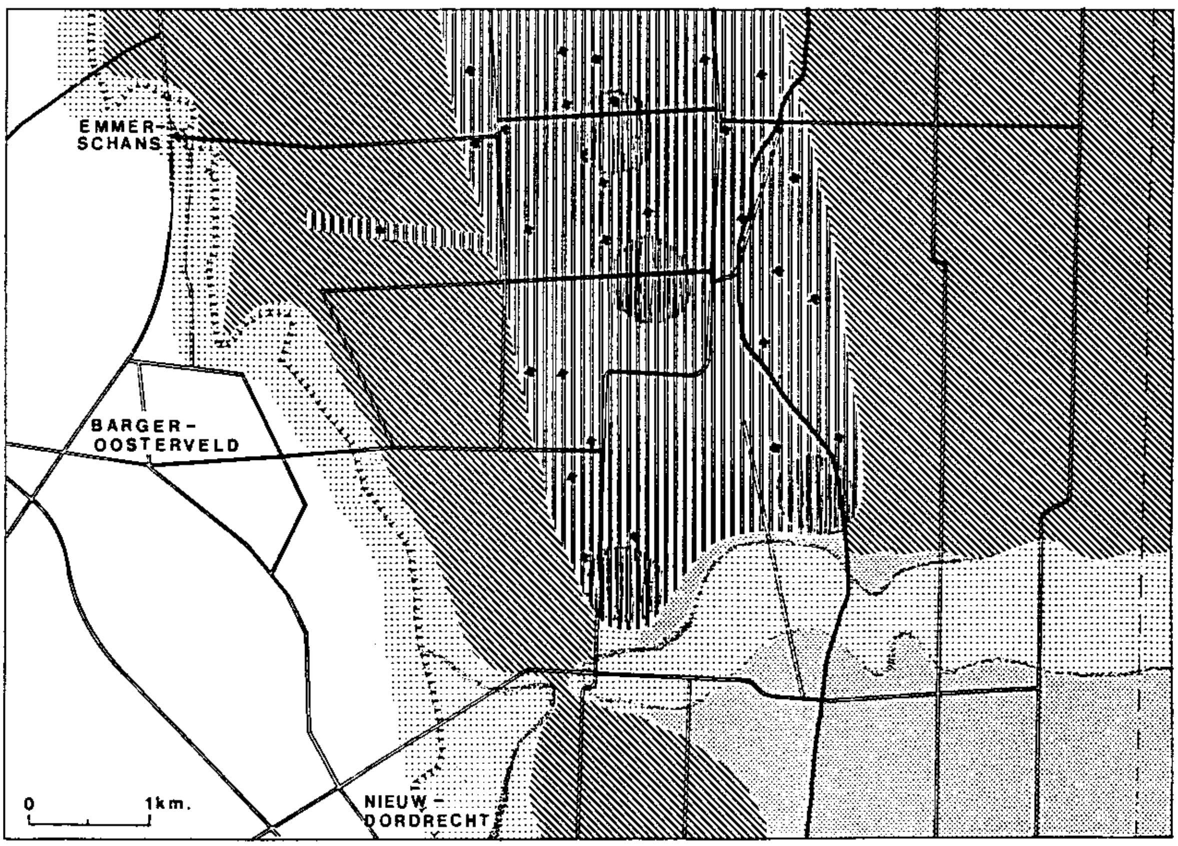


Fig. 12.3

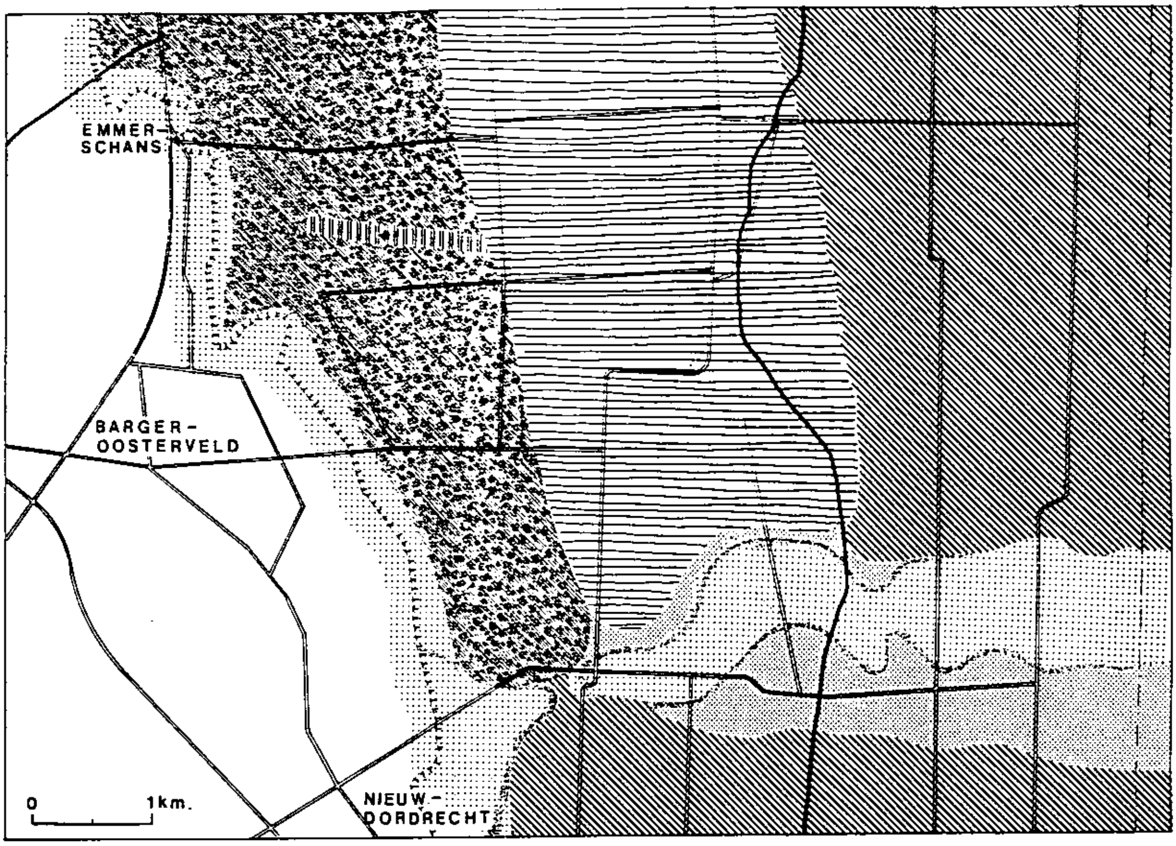


Fig. 12.4

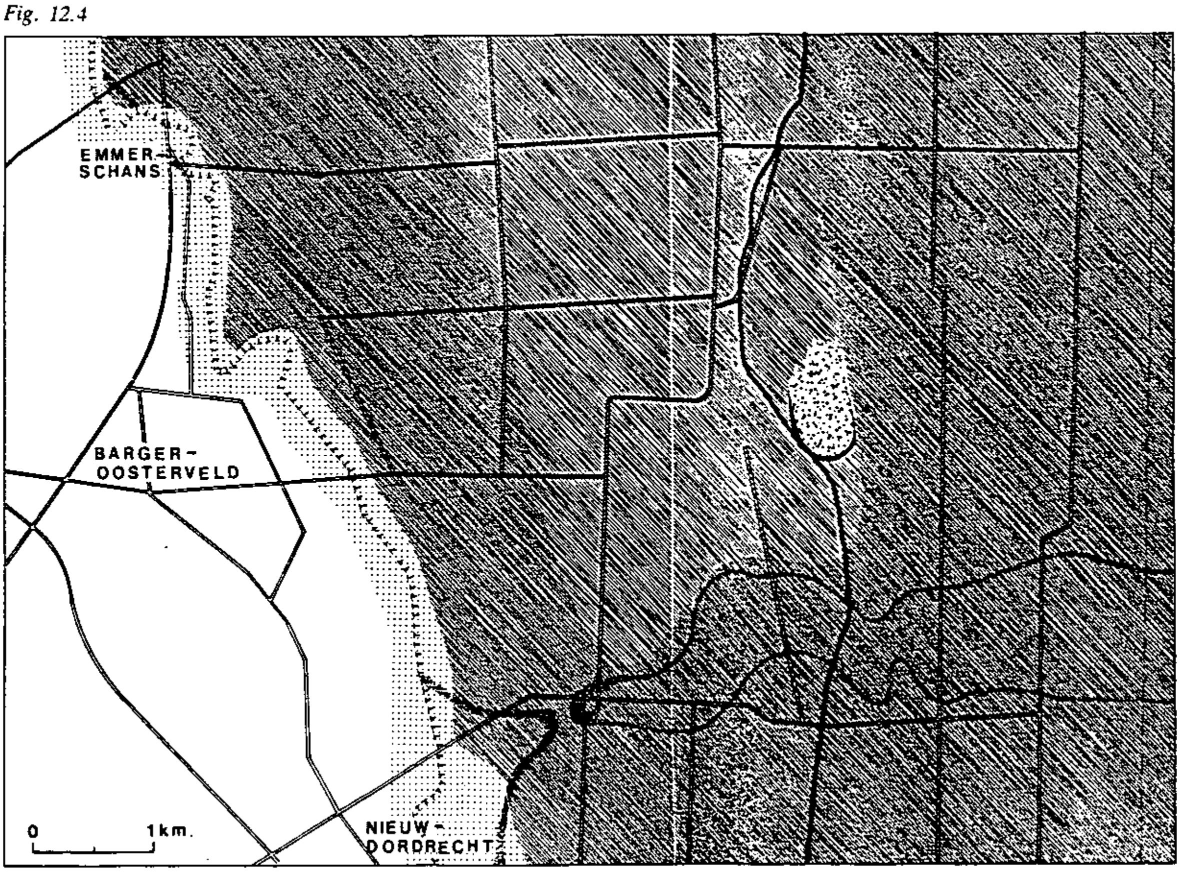


Fig. 12.5

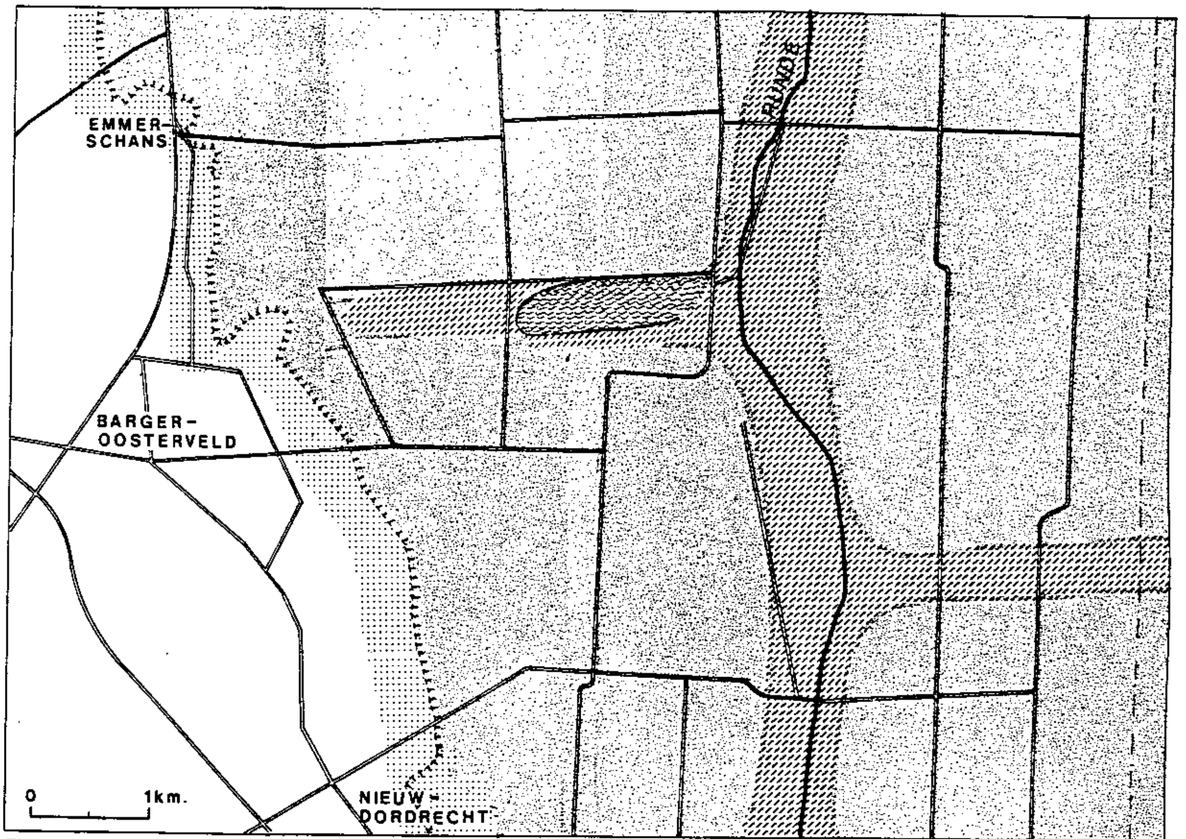


Fig. 12.6

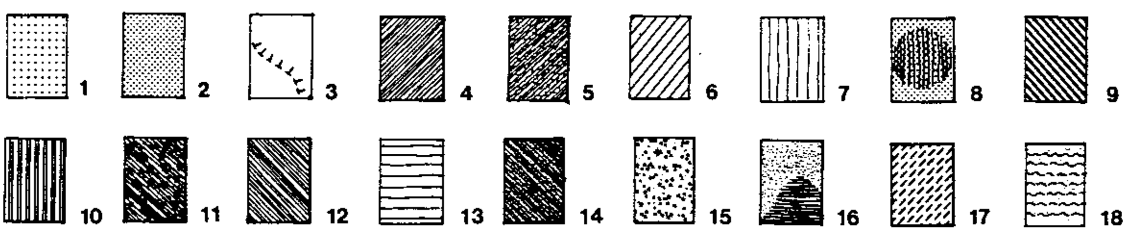


Fig. 12. The spread of peat deposits in the study area, between c. 11,000–500 BC.

12.1: 9000–8500 BC, Hypnaceae peat (German: 'Braunmoostorf') (no. 4), partly covered by the loess layer (no. 5), together situated in the main drainage zone of the southern part of the Hunze valley; 12.2: c. 7000 to 5200–5000 BC, highly humified fen-wood peat (no. 6) now covers a large part of the gully-shaped depression. On the eastern slope of the Hunze valley and the western slope of the Berkenrode ridge, concentrations of water occur, in which sedimentation of gyttja (no. 7) takes place. After stagnation of the water supply, c. 5300 BC, ferruginous seepage comes out of the mineral subsoil, east of the fen peat area, giving rise to the growth of seepage peat with a remarkably high iron content (no. 8); 12.3: between c. 5000 and 3100 BC, iron-poor fen peat, predominantly alder carr (no. 9), borders the seepage peat area (no. 10), that comes into existence downstream from the Postweg ridge and that is fed by four seepage centres (no. 8). The abundance of seepage water causes the development of a vein of ferruginous fen peat in the iron-poor alder carr west of the seepage area. The direction of the water flow in the seepage environment is indicated with arrows. South of the Postweg ridge peat is growing already, firstly fen peat (no. 9), changing in many places into ombrogenous peat; 12.4: between c. 4500 and 4100 BC, a *Pinus* forest (no. 11) develops on top of the alder carr (no. 9), west of the ferruginous seepage peat area (no. 10). This seepage peat dries out c. 3100 BC (no. 12), and as a consequence of this the fen peat growth east of the seepage area (no. 13) comes to an end. South of the Postweg ridge the growth of ombrogenous *Sphagnum* peat predominates; 12.5: between c. 4100, respectively 3100 and 2000–1500 BC, the brown-black highly humified *Sphagnum* peat (no. 13) covers large parts of the study area. The blue-black highly humified *Sphagnum* peat (no. 14) covers the desiccated seepage peat deposits. Just east of this a relatively small strip of iron-poor *Menyanthes-Betula* peat (no. 15), the predecessor of the bog stream Runde, is present. The Postweg ridge is overgrown by ombrogenous peat c. 3000 BC; 12.6:

and *Sorbus*, while *Pinus* is present here and there. Thin charcoal layers indicate the occurrence of – not very extensive – forest fires. It is not clear whether peat also became burnt on these occasions.

Around 5300 BC, by which time a complex of highly humified fen peat almost one metre thick is present, the water supply stagnates once again, now for a period of more than 300 years. The peat forming level then just reaches the level of the threshold in the spillway of the Postwegrug. *Pinus* becomes established on the dry mire surface; the very extensive and presumably also rather dense forest maintains itself for almost four centuries (5300–4900 BC) (Fig. 11C-D, deposit 10). For more than 250 years the pine trees grow relatively slowly and very regularly. At this time the forest soil is rather dry, in view of the extent of the forest fires prevailing in this period. These fires affect the entire area of forest; as a result a layer of peat disappears varying from 10 to more than 60 cm. In the western peripheral area forest fires rage repeatedly, resulting in the development of a remarkably thick layer very rich in charcoal, almost 40 cm thick and containing various black levels. Here a water supply from the Hondsrug is available locally.

The end of this *Pinus* forest occurs as a result of the area becoming considerably wetter once again, as a renewed supply of water starts to flow over the threshold in the cover-sand ridge, c. 5000 BC or slightly later.

3.2.3.3. *The formation of gyttja around the peat deposit* (6800–5300 *BC*)

On the gradual eastern slope of the Hunze valley, in a few shallow east-west gulleys, an orange gyttja layer 10–15 cm thick is found, covered by a thin band of charcoal (Fig. 11C-D, deposit 7; Fig. 12.2). The gulleys measure 10–20 m in width, and 15–30 cm in depth. A grey gyttja with a maximum thickness of 15 cm lies over the orange gyttja and over the low sand plateaus between the gulleys there (Fig. 11C-D, also deposit 7).

The total deposit of orange and grey gyttja has an extent of no more than 1–1.5 km^2. The upward growing peat complex in the Hunze valley (3.3.2.) causes the inundation of east-west gulleys and later also of the intermediate sand plateaus, and consequently the drainage of these gulleys is blocked. This inundation probably also accounts for the occurrence of extensive pools next to the southern flank of the deposit of *Betula* fen-wood peat on the Late Glacial Hypnaceae peat. As this peat is impermeable it prevents the water from soaking away.

The beginning of the gyttja sedimentation can be dated to after 7000 BC, probably around 6800–6600 BC. The thin charcoal layer between the orange and the grey gyttja originates somewhere between 6400 and 5800 BC. The end of the formation of grey gyttja occurs between 5500 and 5300 BC.

The orange gyttja is particularly rich in pollen.

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from 2000, respectively 1500 to 500–100 BC, large areas of ombrogenous *Sphagnum* peat with highly humified hummocks and poorly humified hollows (no. 16) give rise to the development of domed complexes. Between these complexes contact zones with different types of hummocks and hollows (no. 17) occur, in which the superficial runoff of the bog surface takes place. Some of the contact zones contain open water (no. 18), the raised bog lakes. Around 500 BC the raised bog lake in the study area becomes drained by a bog burst.

Key to the maps of Fig. 12.1–12.6: 1. sand; 2. fluvial loam; 3. western bog margin, about 20 m + mean sea-level; 4. Hypnaceae peat (German: 'Braunmoostorf') (c. 11,000–9500 BC); 5. loess layer (c. 9500–8700 BC); 6. highly humified fen-wood peat (c. 8400–5300 BC); 7. gyttja deposit (c. 6800–5300 BC); 8. seepage centres (5200–3100 BC), concentrations of siderite lenses (4500–3100 BC); 9. iron-poor *Alnus* fen-wood peat (alder carr) (5000–4500 BC); 10. ferruginous seepage peat (5200–3100 BC); 11. *Pinus* transitional peat (4500–4100 BC); 12. seepage area, desiccated c. 3100 BC, after which stands of *Pinus* develop locally (3100–3000 BC); 13. brown-black highly humified *Sphagnum* peat (4500–2000 BC); 14. blue-black highly humified *Sphagnum* peat (3100–1500 BC); 15. *Menyanthes-Betula* peat (3100–1900 BC); 16. hummock-hollow systems of the domed complexes, with highly humified hummocks and poorly humified *Sphagnum* peat in the hollows. This is the transition from highly to poorly humified *Sphagnum* peat (2000–500 BC); 17. hummock-hollow systems of the contact zones (from 2000 BC on); 18. open water, in this case a raised bog lake (1500–500 BC).

The palynological data indicate that the gulleys are fringed by vegetation including *Pinus*, *Betula*, *Corylus*, *Quercus* and later also *Ulmus* and *Tilia*. In the water, that was probably only 25 cm deep, *Menyanthes* and *Sparganium* occur; in the bank zone *Salix* is present. Precisely at the level of the charcoal band extensive *Dryopteris* stands are present. To what extent these stands are connected with wide-scale forest fires is not clear. The grey gyttja presumably becomes sedimented in a slightly oxidizing environment. The water depth is possibly hardly 20 cm. Black, oxidized peat mud is floating in the shallow water. *Sparganium* expands markedly in this environment.

The end of this gyttja formation is undoubtedly connected with the drying out of the mire area to the north of the Postrugweg, after the water supply via the spillway in this ridge comes to a standstill c. 5300 BC (3.2.3.1.).

3.2.3.4. *Alnus fen-wood peat and Pinus transitional peat* (5000–4100 *BC*)

Around 5000 BC, on top of the *Pinus* wood peat layer (5300–4900 BC), two completely different types of peat develop, depending on whether the water is poor or rich in iron. In the western part of the mire, over a width of 1.5–2 km, *Alnus* becomes established (Fig. 11D-F, deposit 9; Fig. 12.3). The water supply via the spillway is evidently available once again and the mesotrophic fen peat growth recovers. Between 5000 and 4500 BC the deposition occurs of a moderately humified *Alnus* fen-wood peat with numerous wood remains, measuring 1.0–1.3 m in thickness. This peat formation occurs under conditions of a supply of water poor in iron.

Hypnaceae peat in an iron-rich environment (3.2.3.5.) overgrows the eastern 400–800 m of the *Pinus* wood peat layer and the gyttja deposits lying to the east of it (3.2.3.3.) as well as the eastern gradual slope of the bed of the Hunze. The iron-bearing peat complex extends over a width of 2.5–3 km.

A composite type of topogenous and soligenous peat develops in the more than 100-m-wide contact area between the two hydrological systems.

The carr forest in the western iron-poor part of the study area initially consists almost exclusively of *Alnus* trees; the enormous accumulation of organic material (about 1 m of peat in 500 years) is indicative of optimal peat-forming conditions in a very wet environment with a rapidly rising water level. Partly on the basis of stratigraphic observations, we assume that the alders stand on root stools and are thus able to survive the undoubtedly extensive inundations. Extensive stands of i.a. *Menyanthes*, *Phragmites* and *Dryopteris* develop in the numerous pools and streams in this carr forest. Also *Nymphaea* occurs. In the forest itself *Hedera*, *Frangula* and *Sorbus* are present. Notably in the westernmost, slightly drier part *Pinus* is able to become re-established in a few places.

The peat-forming environment gradually becomes more oligotrophic, as is evident from the occurrence of *Betula*, *Polytrichum*, *Scheuchzeria palustris* and *Sphagnum* in the uppermost 20–35 cm of the fen-wood peat complex. This indicates a greater influence of the direct precipitation in addition to the overabundant supply of water via the spillway in the Postwegrug. Here the water level rises more than 1.20 m between 5000 and 4500 BC, after which period this rise in water level ceases within a relatively short time.

Around 4500 BC a reasonably varied carr forest is present, with *Alnus* as the most important tree species, with *Betula* fairly abundant, here and there *Pinus*, and small to rather large expanses of *Scheuchzeria palustris*, *Carex limosa*, *Phragmites australis* and *Sphagnum*, including *S. cuspidatum*, in wet places and *Calluna vulgaris* and *Empetrum nigrum* in somewhat drier spots. Where the forest soil becomes enriched because of oxidation of the peat, species such as *Rumex* become established. The total forest, measuring about 10 km^2, is dissected by a few shallow gulleys 100–200 m wide holding ferruginous water, with abundance of Hypnaceae. The influence of the water chemistry on the vegetation is considerable, because neither *Alnus* nor *Betula* is able to grow here.

A 10–15 cm thick layer of *Pinus* wood peat lies on top of this *Alnus* fen-wood peat complex; in peripheral parts of the bog and above sand hillocks in the subsoil the layer can be up to 75 cm thick. Here it is often possible to discern a number of wood levels. The layer consists of tens of thousands of stumps with characteristic horizontal root systems, together with bark remains, pine needles, remains of Ericaceae and especially of *Scheuchzeria palustris* (Fig. 11E-F, deposit 11; Fig. 12.4). The growth of the pines is very irregular, which indicates wide fluctuations in the water content of the forest soil. This *Pinus* vegetation can be dated to between 4500 and 4100 BC. In the western peripheral area and in the eastern peripheral zone near the ferruginous seepage peat (3.2.3.5.) the forest vegetation continues to survive for a few centuries longer.

The forest soil shows a wet-dry pattern as a result of some degree of relief, in which the subsoil relief of the underlying sand is reflected. On the somewhat drier spots *Pinus* is able to grow relatively well; the trees reach an age of more than 100 years on average, at which age the trunk diameter is more than 15 cm. They have extensive horizontal root systems. Some trees attain an age of more than 250 years. In the lower, wetter places the trees grow very slowly, however, and seldom reach an age exceeding 60 years. Their diameter is then usually 5–8 cm. As a result of growth corrections induced by the trees sinking into the soft soil, many of these poorly growing trees develop a curved trunk (sickle-shaped pines). During the first 150–200 years of this period with *Pinus* growth on peat, forest rejuvenation occurs a few times, with intervals of c. 35 years.

At the drier spots the forest has an undergrowth of *Calluna vulgaris*, *Andromeda polifolia*, *Vaccinium uliginosum*, *Vaccinium vitis-idaea*, and *Oxycoccus palustris*. Also *Empetrum nigrum* may be present. At the wetter spots *Pinus* trees often occur in shallow standing water, with an understory of *Scheuchzeria palustris* and *Carex limosa*. In various places *Pteridium* and *Dryopteris* are present. *Sphagnum rubellum* and *S. cuspidatum* become established in this environment; this leads to the formation of ombrogenous peat. For these reasons this wood peat layer can be regarded as *Pinus* transitional peat. The upward growing *Sphagnum* lawns gradually impede the *Pinus* forest.

Between 5000 and 4500 BC there is much water supply in the area. In view of the quality of the *Alnus* fen-wood peat that is growing, there is evidently no influence of nutrient-rich groundwater, as occurs commonly in river valleys. The direct precipitation determines to an increasingly greater extent the water chemistry. This effect is undoubtedly strengthened by the increasing amounts of precipitation. Mainly as a consequence of this, the *Pinus* forest soil becomes so acid after 4500 BC that ombrogenous peat-forming vegetations are able to establish here well.

The width of this area with iron-poor fen-wood peat formation between 5000 and 4500 BC is 400–800 m narrower than that formed before 5300 BC. This can be attributed to the strong ferruginous seepage to the east of the *Alnus* fen-wood peat deposit, as a result of which its eastern border becomes shifted towards the west.

3.2.3.5. *Ferruginous seepage peat deposits* (5200–3100 *BC*)

A 2.5–3 km wide Hypnaceae peat deposit remarkably high in iron occurs to the east of the topogenous iron-poor fen peat deposits described in the previous sections (Fig. 11D-F, deposits 12 and 13; Fig. 12.3). This complex consists of soligenous peat, that develops in a seepage environment, and for which the supply of groundwater comes from the Hondsrug (Fig. 9). As during the transport this water comes into contact with the boulder-clay, it becomes ferruginous and also to a slight extent phosphate-bearing. The water comes out of the soil in the Hunze depression. The infiltration area lies 8–12 km west of the area of seepage peat; the difference in height between the two areas measures 2.5–4 m. The thickness of the soligenous peat complex is very variable, from a few decimetres to more than 1.4 m. In the peat in different places concentrations of bog iron-ore, siderite, are present, sometimes with some vivianite (Fig. 11F, deposit 13; Fig. 12.4), in the form of iso-diametric lenses. The diameter of these lenses varies from 1 to 10 m; their thickness is usually between 10 and 30 cm.

In the study area, the seepage water comes out of the subsoil in four sites. These 'seepage centres' are visible as large concentrations of siderite lenses. The total length of this ferruginous complex is about 8 km; it extends mainly downstream in a northerly direction. The southern border is just to the north of the Postwegrug. The deposit develops downstream from the sand ridge.

The deposit lies (going from west to east) on the charcoal-rich wood peat layer of 5300–4900 BC, on the gyttja layer that is deposited until 5300 BC, on fluvial sand and on fluvial loam. Notably the Late Glacial peat (deposit 3) under the wood peat layer and the fluvial loam (deposit 2) are very impermeable to water. The seepage centres are located precisely in the 400 m wide, permeable strip between these two deposits, and at a spot on the Berkenroderug, where fuvial loam is absent.

The beginning of the seepage peat formation dates back to c. 5200 BC. The seepage undoubtedly becomes possible when there is a fall in the surface water levels as a result of the dry period of 5300 BC. The end of the seepage, and thus of the formation of seepage peat, is dated to 3100 BC. After this date the seepage peat here is superseded by ombrogenous peat.

The most important plant species that form seepage peat are Hypnaceae; *Drepanocladus*, *Polytrichum* and various species of *Carex* occur abundantly. *Betula* and *Alnus* are only present in those places where the iron content of the water is lowest, that is to say outside the main drainage channels of the seepage water in the peat-forming environment. In those places where the iron content is low the peat is also thinner. *Sparganium*, *Rumex*, *Equisetum* and *Melampyrum* are also present in the peat.

The mire surface shows distinct domes above the seepage centres and low ridges, where the drainage channels of the seepage water are situated. The difference in height between the most ferruginous and the least ferruginous spots can amount to 1–2 m. These differences are amplified by the subsoil relief.

The siderite, iron oxide (FeO), and the vivianite, iron phosphate, deposits are present in the peat in a reduced state (Van Bemmelen 1895; Reinders 1896, 1902), enveloped in a matrix of Hypnaceae peat. Siderite oxidizes to Fe_2O_3 in the open air. Siderite and vivianite are formed by micro-organisms under the mire surface, where air cannot penetrate. This is probably 10–15 cm below the peat surface. The mechanism of this process of formation is not well understood. The formation of siderite lags considerably behind the start of the flow of seepage water, and begins from about 4500 BC onwards. It is not known whether this time lag is the result of fluctuations in the intensity of seepage or in the iron content or the trophic state of the seepage water, e.g. as a result of the incipient formation of ombrogenous peat to the west of the seepage area.

The supply of seepage water is generally very abundant. This is indicated by, among other things, the outflow of ferruginous water into the western iron-poor system over an area sometimes exceeding 100 m in width, and by the shifting in a westerly direction of the eastern border of this system over 400–800 m (see also 3.2.3.4.). In the composite zone where the two systems overlap extensive areas of *Scheuchzeria palustris* develop over a width of 100–150 m. Fluctuations in the seepage intensity and fluctuations in the quantity of iron-poor water of the western peat complex are difficult to ascertain here.

The seepage peat contains numerous vertical drying cracks, which extend from the top of this deposit down into the underlying subsoil of fluviatile sand. For the most part they are filled up with the humic colloid dopplerite. The origin of these cracks is associated with the seepage coming to an end around 3100 BC. This cessation of seepage is most probably caused by the sudden emptying of the infiltration area. This resulted in a fall in the water Table of several metres. The original infiltration area now becomes a seepage area, with its water supply coming from the mire area in which the ferruginous seepage peat deposits discussed in this section are situated. As a result, this seepage peat deposit dries out and shrinks, and the hardly plastic peat cracks in the process. A polygonal ground-surface develops in this way.

After the sudden cessation of the seepage the mire surface rapidly becomes very wet as a result of the abundant precipitation. The iron in the uppermost peat layers becomes washed out. *Scheuchzeria palustris* become established together with *Sphagnum cuspidatum* in the wettest spots. In the somewhat drier spots, where the iron content is lower, *Pinus* appears. *Sphagnum rubellum* soon arrives and within a century the seepage peat is already largely covered with ombrogenous peat. The dopplerite in the drying cracks probably originates as a result of the ombrogenous peat becoming washed out in the course of the following centuries.

3.2.4. *Ombrogenous peat (from 4500 BC on)*

3.2.4.1. *Introduction*

The ombrogenous peat formations consist primarily of a complex of brown-black highly humified *Sphagnum* peat (4500–2000 BC), that is deposited on top of the *Alnus* fen-wood peat and especially on the *Pinus* peat (3.2.3.4.), and a complex of blue-black highly humified *Sphagnum* peat (3100–1500 BC), situated on top of the ferruginous seepage peat deposit (3.2.3.5.). These deposits have been designated according to the colour of the peat observed during the field research. On the extreme eastern side of the study area there is a complex of *Menyanthes-Betula* peat (3100–1900 BC), that is also classified here as an ombrogenous formation.

Hummock-hollow systems are present throughout the whole area of ombrogenous bog. The earliest formation of poorly humified *Sphagnum* peat occurs in the hollows from c. 2000 BC on. We take this as the upper limit of the brown-black peat deposit. In the blue-black deposit this development starts around 1500 BC. The deposition of this type of peat, in which in addition to the poorly humified hollow-peat also highly humified hummock-peat is present, lasts until the beginning of the Christian Era. In the western peripheral area wood peat still develops after 4500 BC, in which *Pinus*, *Betula* and *Alnus* are important species. Here the peat formation is only partly ombrogenous. Fig. 11E-F shows cross-sections through the peat stratigraphy between 4500 BC and AD 100; the horizontal distribution of these deposits is shown in Fig. 12.4–6.

The formation of ombrogenous peat continues until the bog was drained to facilitate peat digging, after the 17th century of this era. As a result of the practice of drainage and subsequent burning of the bog surface prior to growing buckwheat, all the peat that had formed after the beginning of the Christian Era has disappeared. Consequently, no information is available concerning the peat development since that time.

The process of ombrogenous peat formation is accompanied by the development of spatial structures, such as domed complexes, contact zones, lakes, pools, streams and small rivers commonly occurring in raised bog. These structures govern the water supply; they influence the hydrology of the raised bog to a great extent and are necessary conditions for ombrogenous peat formation. From 4500 BC on the study area is subdivided into two hydrological systems: a western ombrogenous system and an eastern solígenous seepage system. After 3100 BC the whole area can be regarded as a single hydrological system.

3.2.4.2. *The hydrological development: outline of the ombrogenous water supply (from 4500 BC)*

After 5000 BC or slightly earlier the climate in the Netherlands is suitable for the growth of ombrogenous peat (3.1.4.1.). In the study area, at that time already a hydrological regime exists that permits the transition from the growth of fen peat into the formation of raised bog with *Sphagnum rubellum* and/or *S. fuscum* as the principal species forming the peat (Streefkerk &

Casparie 1989). The formation of ombrogenous peat first takes place around 5000 BC in the upper course of the Hunze, oligotrophic conditions being present here at that time (Dupont 1987). The formation of raised bog initially occurs at a very slow rate; a sufficient surplus of water to cause the oligotrophic water to flow away via the spillway in the Postwegrug occurs only towards 4500 BC or shortly afterwards. This influences to an increasing extent the peat-forming environment in the *Alnus* fen-wood peat (3.2.3.4.). Although this water supply is subject to wide fluctuations, with the mire surface repeatedly drying out somewhat, little is known about the frequency and the extent of these instances of drying-out. Fluctuations in the precipitation are probably also important here; hardly any data are available, however.

The Postwegrug becomes overgrown by *Sphagnum* peat around 3300 BC. The drainage of the ombrogenous peat deposits in the upper course of the Hunze now gradually extends over a considerably wider area than the spillway. The resulting drainage pattern becomes manifested only well after 3000 BC. The principal feature is a considerable shifting of the main drainage in easterly direction, towards the (later) course of the raised-bog stream Runde. This process probably does not reach completion until between 2000 and 1500 BC.

The sudden cessation in the seepage in the eastern part of the study area around 3100 BC causes only limited drying-out phenomena in the western brown-black ombrogenous deposit. These phenomena are superficial and are characterized by a decrease of the wet *Scheuchzeria* stands and an expansion of *Pinus* in the contact area of the two hydrological systems.

Around 2500 BC part of the eastern blue-black deposit becomes drained via the drying cracks in the underlying seepage peat deposit. This causes a desiccation to a considerable depth over a surface area of 4–6 ha. Subsequently, the depression resulting from shrinkage because of this desiccation, fills up with stagnant water. This drainage is discernible over an area of more than 400 ha as a slight, superficial desiccation.

After the peat becomes somewhat drier in c. 2200 BC, around 2000 BC the area becomes distinctly wetter, as a result of higher precipitation and slightly declining temperatures. This leads also to increased air humidity. From this time on the influence of these climatic factors on the peat development in the study area is more clearly recognizable. Dupont (1985) demonstrates a succession of somewhat wetter, sometimes very wet, and drier phases up until the beginning of the Christian Era.

Between 1700 and 1200 BC circumstances are somewhat drier. Around 1200 BC parts of the bog surface dry out, and the peat vegetation becomes burnt locally. Between 1200 and 700 BC somewhat wider fluctuations in precipitation and temperature occur, with the mean temperature c. 850 BC declining by about 1°C. At this time once again a (brief?) period of drying-out occurs. Afterwards the peat becomes considerably damper again. From 600–300 BC the weather is somewhat warmer again, with fairly high quantities of precipitation. After the beginning of the Christian Era the weather becomes somewhat cooler while the precipitation is still relatively abundant. This information, which is derived from the peat region in the upper course of the Hunze, corresponds well to what can be deduced from the peat stratigraphy in the study area.

This climatic development ultimately results in the bog becoming increasingly wet. This influences the peat formation and the development of spatial structures in the peat.

3.2.4.3. *Hummock-hollow systems, domed complexes and contact zones*

Four types of hummocks and hollows can be distinguished in the raised-bog area, see Fig. 13 (Casparie 1972). The previously used names are mentioned between brackets after the numbering used here. Type I (Emmen 9) is the peat of the domed complexes; type II (Emmen 17) develops in those contact zones between the domed complexes in which there is much accumulation of water, but only relatively little water flow. Type III (Emmen 22 + 23) consists of the marginal

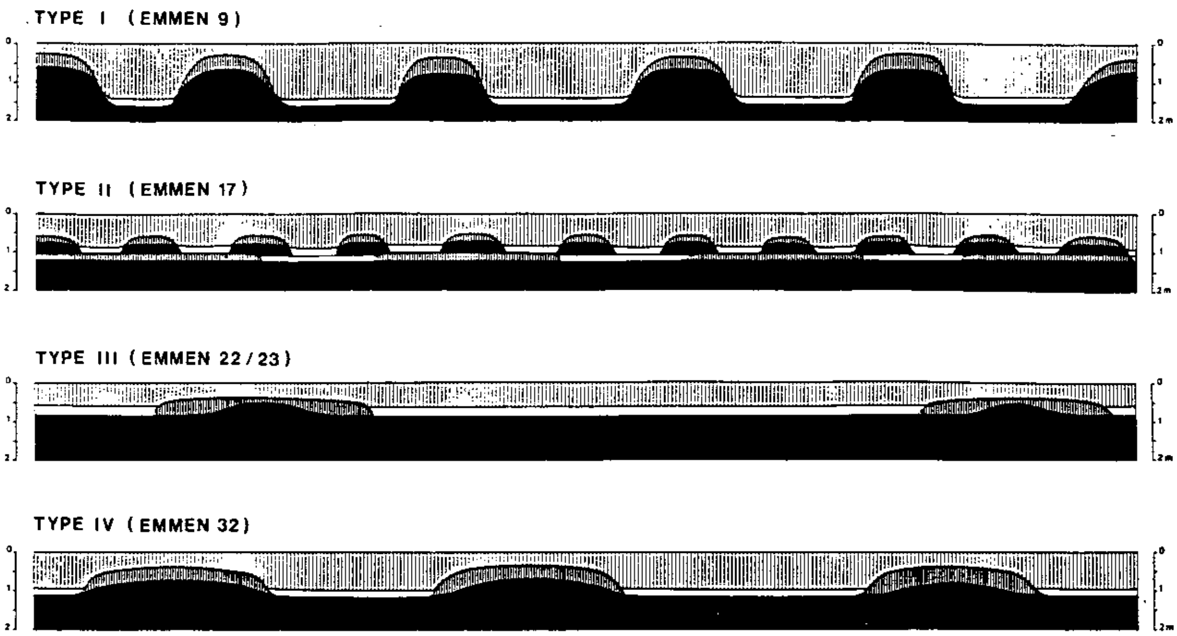


Fig. 13. Schematic representation of the four hummock-hollow types distinguished in the study area, given as cross-sections. Symbols: black: highly humified *Sphagnum* peat: narrow hatching: moderately humified *Sphagnum* peat; wide hatching: poorly humified *Sphagnum* peat; white: poorly humified *S. cuspidatum* peat. The type names in brackets refer to Casparie (1972).

area of a large raised-bog lake in a west-east contact zone, in which also type II is present. Type IV (Emmen 32) occurs especially in the south-north contact zones which have a high water flow.

In the hollows of type I *Sphagnum cuspidatum* and *S. papillosum* become established, which marks the beginning of the formation of poorly humified peat. The growth of this type of peat takes place somewhat more rapidly from c. 2000 BC on, resulting in the development of the 'domed complexes' (Fig. 14), associations of hummocks and hollows of type I. The domed complexes have a diameter of 3–4 km; they grow most rapidly in the middle. Around 1500 BC there is such a difference in height with respect to the surrounding contact zones that the water surplus can no longer be held in the hollows. The water surplus, that causes permanent inundation of the hollows of type I between 2000 and 1500 BC, now flows away peripherally to the lower lying contact zones. The formation of *Sphagnum cuspidatum* peat in the hollows stagnates as a result of this.

The flow of water from the type I hollows to the type II hollows in the contact zone, from c. 1500 BC on, permits the formation of poorly humified *S. cuspidatum* peat in this zone. As a result of this hydrological development, around 1500 BC, the smoother hummock-hollow system of type II is superseded by a more pronounced hummock-hollow topography, in which the formation of poorly humified *S. cuspidatum* peat continues in inundated hollows (3.2.4.7.). Both of these hummock-hollow systems are included in type II.

The 200–300 m wide contact zones become very wet as a result of the supply of surplus water from the domed complexes. This water stagnates in the west-east contact zones. Where they are situated in the area of the blue-black *Sphagnum* peat deposit (3.2.4.5.), situations occur in which type III can develop characterized by large hollows, with poorly humified peat. As a result of the permanent inundation a raised-bog lake develops in a west-east contact zone after 1500 BC. This lake probably had no or only a very insignificant drainage outlet. The stagna-

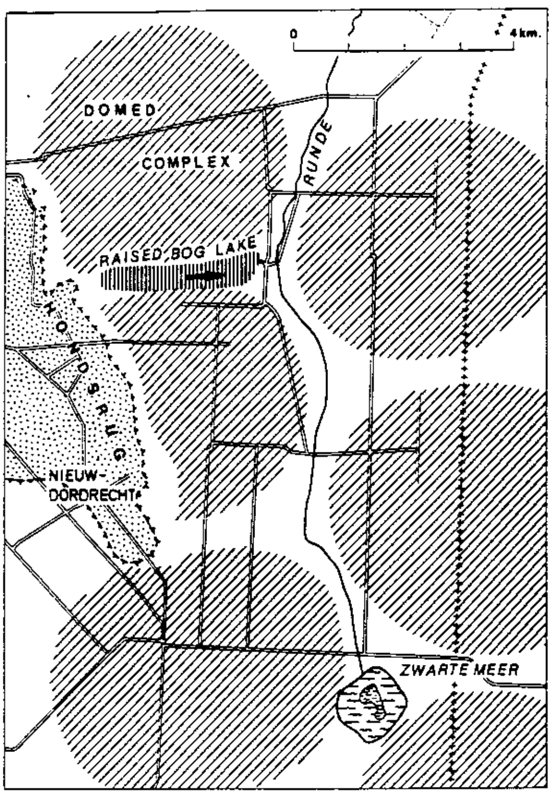


Fig. 14. Bourtanger Moor in the northeastern Netherlands, situation of the presumed domed complexes since c. 1500 BC, existing largely of hummock-hollow type I. The contact zone with the raised bog lake and the hummock-hollow type II has been indicated by vertical hatching. The arrow in the lake gives the direction of the water flow of the bog burst dated to c. 500 BC. The bog stream Runde develops in the south-north contact zones, with its source in the Zwartemeer, a bog lake between three domed complexes. Dotted area: upland soils.

tion is possibly attributable to the occurrence of a seepage-peat dome (3.2.3.5.) located at the eastern end of this contact zone. As a result of the stagnation the water level in the raised-bog lake rises gradually. In this extremely wet environment c. 25 cm thick deposits of *Sphagnum cuspidatum-Scheuchzeria palustris* peat develop. Type III comprises the fringe area of this raised-bog lake.

In the gently sloping south-north contact zones a drainage system gradually develops, classified as type IV. This type is characterized by the repeated occurrence of slight, superficial erosion. The raised-bog stream Runde originates from this system.

A formation of highly humified peat in the contact zones points to a relatively dry period around 1200 BC. Subsequently, after a few decades the entire peat area becomes considerably damper. The raised-bog lake expands markedly; its surface area is ultimately c. 30 ha. It obtains its water from three domed complexes, the total area draining into this lake extending over c. 1000 ha. About 850 BC there is a brief drier period once again. The subsequent increase in precipitation makes the whole mire surface considerably wetter. On the domed complexes this leads to the deposition of poorly humified peat, in which *Sphagnum imbricatum* and *S. papillosum* become steadily more important. The water level in the raised-bog lake continues to rise. About 500 BC the lake bursts through its weakest bank, after which it drains towards the east into the south-north contact zones that ultimately drain towards the north.

This bog burst (German: 'Moorausbruch') is accompanied by the development of extensive 2 m deep erosion gulleys in the peat layer beneath the raised-bog lake. This catastrophic erosion involves not only the study area, but also the part of the Bourtanger Moor situated upstream, measuring about 20 km^2 (Dupont 1986).

The considerable fall in the water level resulting from this drainage does not lead to drying-out of the mire surface to any great depth. Within a short period the water level is sufficiently high again for peat accumulation to become re-established. On account of the substantial discharge of water, in which relatively many minerals are present, the area becomes considerably more oligotrophic. This stimulates the deposition of fresh and poorly humified peat, formed by *Sphagnum imbricatum* and *S. papillosum*. About 300 BC these are the predominant peat-forming plant species; the pattern of hummocks and hollows of the domed complexes (notable type I) remains unchanged after this development. Shortly afterwards, possibly around the beginning of the Christian Era, highly humified *Sphagnum* peat is deposited once again in the contact zone, formed mainly by *S. imbricatum*. In this zone the hummock-hollow system (type II) now changes again, but it is not clear how this development continues, as no further stratigraphic information is available.

The erosion gulleys, that were formed in the peat around 500 BC, continue to function after this time. At this stage the raised-bog stream Runde, that originates from the raised-bog lake Zwarte Meer, starts to take its final course in the south-north contact zones (Fig. 14).

3.2.4.4. *Brown-black highly humified Sphagnum peat* (4500–2000 *BC*)

Around 4500 BC, ombrogenous peat-forming species, notably *Sphagnum rubellum*, become established in the *Pinus* forest on top of the *Alnus* fen peat. This development occurs especially near the very wet spots in this forest, where *Scheuchzeria palustris* and *Sphagnum cuspidatum* are also dominant. The highly humified ombrogenous peat deposit that forms in this way overgrows the last remains of this *Pinus* forest around 4100 BC. The end of the formation of this type of peat can be dated to 2000 BC, when the deposition of poorly humified *S. cuspidatum* peat begins in the hollows.

The brown-black highly humified peat deposit has a width of c. 2.5 km, corresponding to that of the iron-poor *Alnus* fen-wood peat on top of which it develops. The thickness of the deposit is 60–80 cm (Fig. 11E-F, deposit 15; Fig. 12.5).

The most important peat-forming species is *Sphagnum rubellum*, while *Calluna vulgaris* and *Eriophorum vaginatum* are also present in abundance. The stratigraphy of this deposit is conspicuously layered, sometimes with distinct layers with much *Pinus*. These trees usually attain an age of a few decades. Around 2500 BC, *Empetrum nigrum* expands markedly in part of this deposit. This plant community maintains itself for a few centuries and as a result of the drainage of part of the adjacent blue-black peat deposit, that causes slight shrinkage here. Water soon collects in the developing depression so as to form an environment eminently suitable for the growth of *Empetrum*. The presence of a vein of ferruginous Hypnaceae peat precisely at this spot may have contributed to the formation of this environment. This type of peat is indicative of the discharge of ferruginous water and is formed between 4500 and 3100 BC, as mentioned in 3.2.3.5. Here and there expanses of *Polytrichum strictum* are present. The conspicuous layering of the deposit indicates fluctuations in the water level during the process of peat formation.

The peat-forming environment shows patterns of hummocks and hollows; the latter contain open water only to a very limited extent. Here *Sphagnum rubellum* is not only a hummock former but also an occupant of hollows. *S. cuspidatum* layers, indicative of inundated hollows, occur very scarcely. The slope of the peat-forming surface, with a gradient of probably 0.4 promille towards the north, permits water flow to such an extent that inundation does not occur.

The brown-black peat deposit is characterized by relatively slow accumulation of organic material; the accumulation rate is about half as that in the blue-black deposit. During the peat formation a considerable decomposition of organic material occurs, possibly as a result of oxidizing conditions in the acrotelm. The brown-black ombrogenous system is fed by water from the southern, upstream part of the Hunze valley, where the formation of ombrogenous peat starts already before 4500 BC (3.2.4.2.). The water surplus flows via the spillway in the Postwegrug into this brown-black system. This water supply is actually the continuation of the northward flowing system that fed the topogenous peat formation from the Late Glacial until 4500 BC (3.2.2.1.). Now, however, the water has become acidic and oligotrophic. It has the effect of making the peat-forming top layer richer in oxygen, on account of the long distance over which this surface water supply reaches the brown-black complex. This creates stronger oxidizing conditions.

3.2.4.5. *Blue-black highly humified Sphagnum peat* (3100–1500 *BC*)

This type of ombrogenous peat starts to develop

c. 3100 BC on top of the dried-out seepage peat surface (3.2.3.5.). The peat is poor in iron; despite the richness in iron of the underlying Hypnaceae peat. In the lower part of the area, the base of the blue-black peat consists of a 3–6 cm thick *Scheuchzeria palustris-Sphagnum cuspidatum* layer on top of a dopplerite layer 1–2 cm thick. In the higher parts *Pinus* becomes established very soon after the drying-out of the seepage peat. Within 100 years the scattered patches of *Pinus* forest become overgrown by peat-forming plant communities with dominance of *Sphagnum rubellum*. The deposition of this blue-black highly humified peat comes to an end c. 1500 BC.

The width of the deposit is 2.5–3 km, corresponding to the extent of the underlying seepage peat deposit. It has a mean thickness of 1.20 m, with an occasional thickness of almost 1.80 m (Fig. 11F-H, deposit 16; Fig. 12.5).

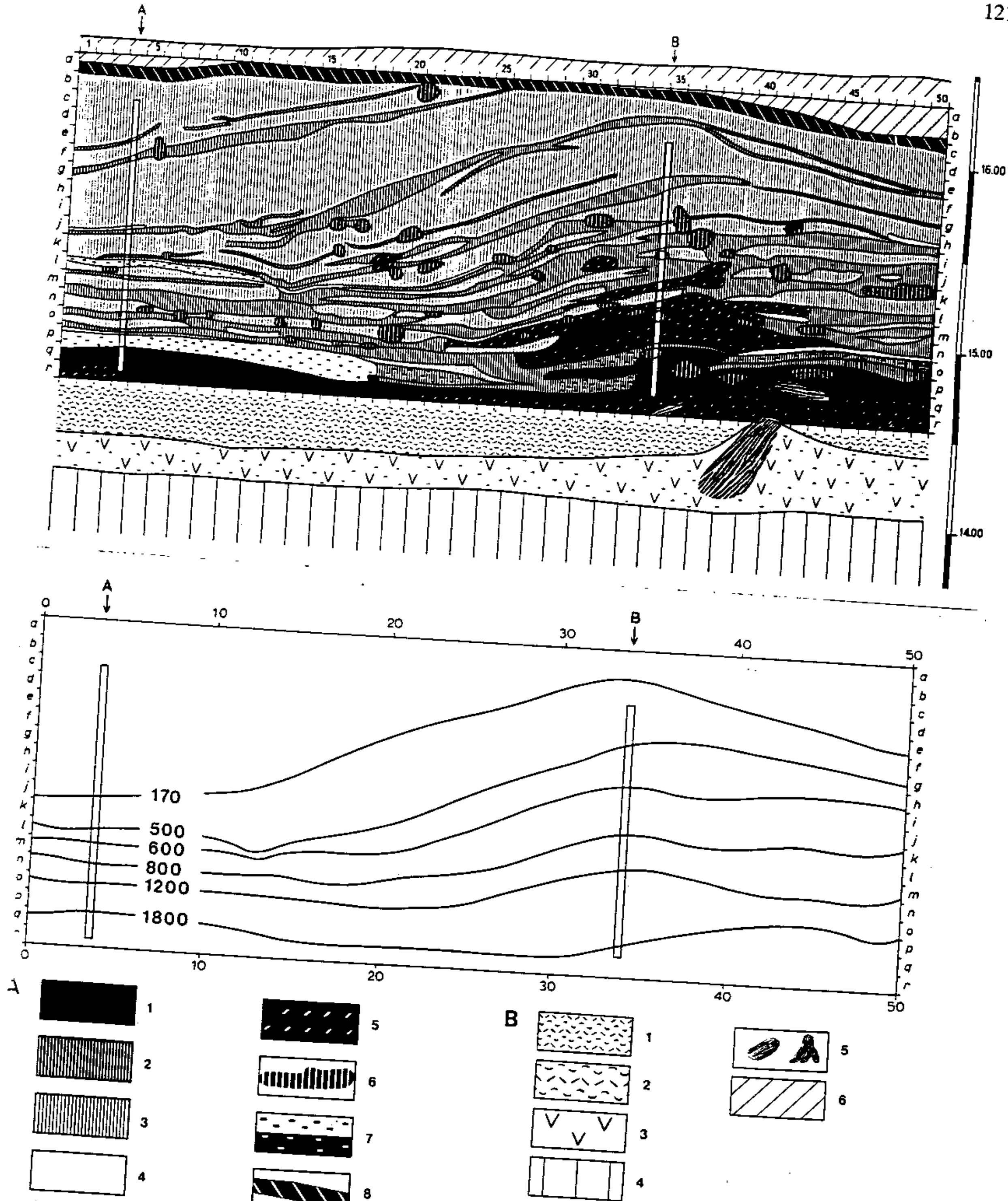
The botanical composition is basically similar to that of the brown-black peat. *Pinus* and *Scheuchzeria palustris* occur much less frequently and *Calluna vulgaris* is somewhat less abundant. *Sphagnum molluscum* and *Aulacomnium palustre* are present more abundantly than in the brown-black peat. Further, the deposit does not show the conspicuous layering characteristic of the brown-black peat. The drainage of an area of 4–6 ha of this peat via the drying cracks in the underlying seepage peat (c. 2500 BC, 3.2.4.2.) leads to *Pinus* becoming established in the peripheral zone of the dried-out area. Within four decades this belt of pine forest becomes overgrown by *Sphagnum*.

From c. 2500 BC on large expanses of *Eriophorum vaginatum* occur. Their distribution is associated with the relief of the peat surface which emerges after the drainage of 2500 BC, and reflects the relief of the mineral subsoil. The shrinkage of the surface following the drying-out later results in the development of large wet patches, in which *Eriophorum vaginatum* predominates. The expanses of these patches are about 100 m wide; one such patch is even almost 500 m wide. The expansion of *Eriophorum vaginatum* is probably connected with somewhat wider fluctuations of the water level in the peat on account of the relief. *Empetrum nigrum* occasionally is also abundant. From 2500 to c. 1800 BC, no hummock-hollow systems develop here.

Around 2000 BC the blue-black peat becomes gradually moister; this results in the appearance of pools, in which *Sphagnum cuspidatum* expands considerably. *S. imbricatum* becomes also established here, but is unable to maintain itself, possibly because the environment is insufficiently acidic. The blue-black character becomes less distinct, and after 1800 BC hummock-hollow systems develop here in which *Calluna vulgaris* predominates in the hummocks. In the hollows, highly humified *Sphagnum cuspidatum* peat continues to be deposited.

The blue-black peat contains much strongly fragmented organic residue. This is noticeable in the much more greasy character of this peat in comparison with the brown-black deposit. Evidently a much higher proportion of the incompletely decomposed peat-forming plants is still present in the substratum. This presumably explains also the considerably more rapid accumulation of organic material in this deposit compared with the brown-black peat. It is assumed that the decomposition of the organic material is slowed down as a result of somewhat more strongly reducing conditions, as may also be indicated by the bluish tint of the peat.

The blue-black deposit originates first more or less behind the Postwegrug, east of the brown-black deposit. This means that little or no water can flow out of the peat developing on the other side of this coversand ridge. This water discharges mainly through the brown-black peat. The blue-black peat develops as it were under the lee of the Postwegrug. At this point in time also the brown-black peat surface lies slightly lower, so that for a long time the main drainage pattern still remains situated west of the blue-black deposit. This ridge does indeed become overgrown by ombrogenous peat-forming vegetations around 3300 BC, but the drainage structures in this highly humified *Sphagnum* peat develop only much later, probably after 2000 BC.



?. *15.* Peat section with hummock-hollow type I (Emmen 9) (upper part) and synchronised lines (lower part) in this section.
ːe section is drawn with a grid with squares of 10 x 10 cm; horizontal 1-50, vertical a-r, measuring 5.0 x 1.8 m. A and B are
·estigated monoliths. The synchronised lines with (rough) datings in years BC show the upward growth of the ombrogenous bog
·face with hummock-hollow type I, between c. 2000 BC and the beginning of the Christian Era.

3.2.4.6. *Menyanthes-Betula peat* (3100–1900 *BC*)

This peat lies immediately east of the blue-black highly humified *Sphagnum* peat on top of the dried-out seepage peat surface, on a thin layer of dopplerite. It is poor in iron. The peat formation begins around 3100 BC with *Sphagnum cuspidatum* and *Scheuchzeria palustris*, but soon peat is being formed in which *Menyanthes trifoliata* and *Betula* play an important part. It appears to be a kind of fen-wood peat, in which *Sphagnum rubellum* cannot develop until c. 1900 BC, which dates the end of this type of peat. The width of the deposit is approximately 500 m; the thickness varies from 0.90 to 1.20 m (Fig. 11F-H, deposit 14; Fig. 12.5). A layer very rich in wood (*Betula*) is present, indicating drier conditions between 2500 and 2400 BC. These drier conditions are almost certainly due to the drainage around 2500 BC of part of the blue-black peat (3.2.4.2.).

The combination of *Menyanthes trifoliata* and *Betula* with *Aulacomnium palustre*, *Polytrichum* sp., cf. *Drepanocladus*, *Dryopteris* and *Rumex* occurs only in this deposit. On both margins expanses of *Eriophorum vaginatum* are present, that are able to maintain themselves from c. 2500 BC until after 1900 BC.

The *Menyanthes-Betula* peat develops, with a brief interruption between 2500 and 2400 BC, into a very damp to wet environment. It becomes fed not only by direct precipitation but also by the water surplus from the surrounding ombrogenous peat deposits. The water is mesotrophic to oligotrophic, and until 1900 BC it is insufficiently acidic for *Sphagnum* growth. There is a great accumulation of organic material. The richness in iron of the underlying Hypnaceae peat has no influence on the formation of this iron-poor peat.

3.2.4.7. *The transition from highly to poorly humified Sphagnum peat* (*from* 2000 *BC on*)

The transition from highly to poorly humified *Sphagnum* peat does not strictly concern a separate deposit but nevertheless can be defined spatially and genetically as well as in terms of dating. The lower limit is the first deposit of poorly humified *Sphagnum cuspidatum* peat in hollows, and the first occurrence of *S. imbricatum* and *S. papillosum*, dated to 2000 BC. The upper limit is put at the ultimate coverage of the highly humified *S. rubellum* hummocks by poorly humified *imbricatum-papillosum* peat. This occurs especially between 500 BC and the beginning of the Christian Era.

This transition is closely connected with changes in the hydrological conditions in the region (3.2.4.2). In this section emphasis is laid particularly on the peat-forming vegetation and the actual peat growth. In the vertical peat-faces the transition can be recognized in the remarkable picture of highly humified hummocks and poorly humified hollows next to each other. This is shown schematically in Fig. 13.

In the hollows of the raised bog complex, that resulted in the brown-black *Sphagnum* peat (3.2.4.4.), poorly humified *Sphagnum* peat is deposited from c. 2000 BC on. This deposit eventually expands over a period of 1200–1800 years so as to cover almost the whole peat surface (Fig. 11G-J, deposits 17 and 18; Fig. 12.6). The first formation concerns a 5–15 cm thick layer of poorly humified peat of *Sphagnum cuspidatum* and *S. papillosum*, with occasionally some *Scheuchzeria palustris* that is deposited in the hollows after they become slightly inundated. The open water, which has a depth of 10 cm at most, disappears about 1500 BC, but the hollows remain very damp. Now *S. papillosum*

A: types of peat in the grid with 10 x 10 cm squares: 1. highly humified *Sphagnum* peat; 2. moderately humified *Sphagnum* peat; 3. poorly humified *Sphagnum* peat; 4. *Sphagnum cuspidatum* peat, generally fresh or slightly humified; 5. *Calluna-Sphagnum* peat; 6. *Eriophorum vaginatum* peat; 7. *Scheuchzeria* peat, poorly or highly humified; 8. buckwheat layer (arable).

B: peat types outside the grid; 1. highly humified *Sphagnum* peat; 2. poorly humified *Sphagnum* peat; 3. wood peat, pine stumps layer; 4. fen peat and fen-wood peat; 5. *Pinus* stumps; 6. secondarily weathered (topmost) peat layer, tilth (disturbed peat).

becomes the most important peat-forming species here.

On the hummocks the formation of highly humified *Sphagnum* peat by *S. rubellum*, *Calluna vulgaris* and *Eriophorum vaginatum* continues. On the flanks of the hummocks – probably just above the water level in the hollows – *S. imbricatum* forms moderately to poorly humified peat deposits, often in conspicuous cushions. In Fig. 15 an example of this hummock-hollow system is shown (type I, Fig. 13).

From 2000 BC on, large flat hummocks of moderately humified peat of *Sphagnum rubellum* and *S. molluscum*, with remarkably little *Calluna vulgaris* and *Eriophorum vaginatum* are formed on top of part of the brown-black peat. In the hollows, poorly humified *S. cuspidatum* peat is deposited. This formation, measuring 10–20 cm in thickness, is the lowermost hummock-hollow system of type II (Fig. 13). A system with more pronounced, smaller hummocks with *S. rubellum* and much *Eriophorum vaginatum* and *Calluna vulgaris* replaces the flat system around 1500 BC. In the hollows the formation occurs of poorly humified *S. cuspidatum* peat. These hollows and hummocks, the uppermost system of type II, maintain themselves until a few centuries before the beginning of the Christian Era.

S. imbricatum expands at the cost of *S. rubellum* on the flanks of the hummocks after c. 900 BC; this is accompanied by the formation of moderately humified peat. The proportion of *Calluna vulgaris* and *Eriophorum vaginatum* in the vegetation decreases. The transition from a flat to a more pronounced hummock-hollow system is related to the development of the contact zones and the peripheral drainage pattern on the raised-bog surface (3.2.4.3.).

From c. 1500 BC on, in the hollows in the blue-black *Sphagnum* peat of the raised bog complex (3.2.4.5.) poorly humified peat is deposited as well. *Sphagnum cuspidatum*, *S. papillosum* and *Scheuchzeria palustris* form a deposit of hollow sediments measuring 5–15 cm in thickness. In the hollows, which clearly have a drainage function, there is rather strong superficial erosion. This results in the hummock-hollow system of type IV (Fig. 13). The geomorphology of this type is different from that of type I; the surface area of the hollows is larger. This is presumably associated with their drainage function.

A 30 ha raised-bog lake (3.2.4.3.) forms on the blue-black peat deposit. The water depth is probably less than 60 cm. In this lake floating expanses of *Sphagnum cuspidatum* and *Scheuchzeria palustris* occur. Hummock-hollow systems of type III (Fig. 12) form along the fairly wide marginal zone of this lake. The hollows are often wider than 10 m.

After a short dry period around 1200 BC the peat becomes much damper once again. This results in the expansion of the bog lake beyond part of the marginal zone with the hummock-hollow system of type III. This leads to the deposition of poorly humified *S. cuspidatum* peat with *Scheuchzeria palustris* in the hollows. The thickness of this deposit is approximately the same as that of the corresponding deposits in the raised-bog lake itself: 25 cm. It contains a thin, darker, highly humified layer, indicative of another period of drying-out between 900 and 800 BC. Subsequently, the amount of water at the peat surface once more distinctly increases. This leads to the deposition of poorly humified, very damp *S. papillosum* peat in the hollows and over the edges of the hollows, and the deposition of *S. imbricatum* peat on the hummocks. Fluctuations in the water content are visible as thin layers of *S. cuspidatum* in the hollows as the peat becomes wetter, and as darker, slightly more humified peat layers as the peat becomes somewhat drier.

After the bog burst of 500 BC (3.2.4.3.) the deposition of poorly humified *S. papillosum* peat and *S. imbricatum* peat rapidly continues, notably in the deep erosion gulleys which remain after the drainage of the raised-bog lake. After c. 200 BC, there are hardly any hummocks on the domed complexes with highly humified *S. rubellum* peat mixed with abundant *Calluna vulgaris* and *Eriophorum vulgaris*. This could be called the end of the transition from highly to poorly humified *Sphagnum* peat. In the period from 2000 to c. 200 BC the peat-forming surface rises by 1.00–1.50 m.

The poorly humified *Sphagnum* peat deposit is not discussed separately.

3.2.4.8. *The western marginal area of the mire (from 4500 BC on)*

In the forest along the western bog-margin, that is already present before 4500 BC, *Alnus* remains the most important tree species. The forest maintains itself subsequently, in some places until after 2000 BC. The forest is mostly 100–300 m wide and has similar characteristics as described for the forests at the time of the formation of the *Alnus* fen-wood peat (3.2.3.4.). The forest is clearly influenced by eutrophication from the mineral higher soils of the Hondsrug. The fringe forest gradually becomes poorer in nutrients, as a result of which *Betula* becomes more abundant, from 3000 BC. In addition, fluctuations in the water level of the marginal area are clearly visible in the peat deposit. Where the peat surface becomes drier, woody stands (*Alnus*, *Betula*, and sometimes *Pinus* and *Quercus*) expand further to the east. Increasing dampness leads to the development of extensive pools in this zone, in which such species as *Phragmites australis*, *Typha* and *Iris pseudacorus* become established. This formation is not indicated separately in the cross-sections of Fig. 11.

Along the bogward side of the *Alnus* carr, forest complexes of *Pinus* can maintain themselves in various places after 4500–4100 BC. *Scheuchzeria palustris* is abundant in this marginal area, especially after 3000 BC. This is indicative of reclamation activities on the higher soils west of the bog. As a result of these activities dust and ash evidently became blown into the peat, while the clearance of forest by means of felling trees influenced the water regime of the bog margin.

The influence of the upward-growing ombrogenous peat (3.2.4.4.) becomes clearly visible particularly after 2200 BC. The bog-marginal forest, in which *Alnus* predominates, becomes considerably narrower, and is partly replaced by *Pinus* and *Scheuchzeria palustris*. As a result of the increasing capacity of the ombrogenous peat for holding water, these communities are ousted towards the west by the expansion of the brown-black peat-forming *Sphagnum* stands. *Pinus* is still able to maintain itself in the actual bog margin. This belt of forest grows upward together with the upward growing peat along the mineral bog margin, with *Scheuchzeria palustris* still forming part of the vegetation. As the bog margin dries out somewhat, *Pinus* regains part of its lost territory to the east. This process continues until after 500 BC. No information is available on younger deposits, as these have disappeared.

The steep western mineral slope shows a heavy podzol, which is characteristic of soils on which ombrogenous peat formation takes place. Here the podzol is present mainly underneath the forest peat that directly overlies sand. The thickness of this peat podzol, with a very heavy and hard brownish iron-pan, is often more than 50 cm.

3.2.5. *Some reflections on the dynamics of the water balance in situations with ombrogenous peat growth*

3.2.5.1. *Hydrological aspects of the growth of ombrogenous peat*

The development of the spatial structures mentioned in 3.2.4.3. is directly related to the water supply of this system, as described in 3.2.4.2. The water regime of the ombrogenous system discussed in the previous sections, can be broadly outlined as follows.

Bog water from the hollows of the domed complexes collects in the somewhat lower lying marginal contact zones. This water has no direct function any longer to the formation of ombrogenous peat. It maintains the water-saturated condition of the underlying peat deposit, in which almost no biological processes take place. In this sense the 'catotelm' is persistently wet (Ingram 1983).

The water that enables the ombrogenous peat formation is in the first instance contained in the hollows of type I of the domed complex. The centrifugal discharge of this water forms a supply of water to the living mire vegetation, in which peat is formed. In periods without precipitation the high water level can be maintained by the sagging of the peat surface (German: 'Mooratmung') that accompanies the substantial evaporation during the vegetation period. The water level in the bog vegetation remains high as a result of this.

On the domed complexes water also collects in a different way, to form bog pools that are considerably larger than the hollows. These pools, that sometimes measure several tens of metres in diameter (Dutch: 'meerstallen') are sometimes present in large numbers, precisely on the highest part of the domed complexes. They are fed exclusively by direct precipitation and their origin is due to the very slow rate of flow of the drainage system over the domes. Here the gradient is so gradual that the water flowing out via the hollows is available for sufficiently long a time to allow peat formation. The bog pools develop only at a late stage in the study area, possibly not until a few centuries after the bog burst of 500 BC. The water that is not taken up in the bog vegetation initially remains in the hollows. In this environment thin *Sphagnum cuspidatum* layers develop. As the body of water increases a number of these hollows gradually expand into bog pools.

The central part of the domed complexes probably lies 3–4 m higher than the periphery formed by the contact zones. The gradient here is about 0.4 promille; evidently this results in a sufficiently slow discharge of superficial water to permit the formation of ombrogenous peat to be maintained. Near the contact zone the slope is somewhat less gradual. The system of ombrogenous peat growth is thus characterized by a water surplus on the peat surface, which situation is partly maintained by precipitation and partly by the slow flow of surface discharge water; this is called 'system-linked discharge' (Dutch: 'systeemgebonden waterafvoer') (Streefkerk & Casparie 1987, 1989).

3.2.5.2. *System-linked water discharge*

From the peat research in the Netherlands, of which the results are described in this chapter, and from supplementary research (Streefkerk & Oosterlee 1984; Dupont 1986; Streefkerk & Casparie 1987, 1989) it is possible to work out the dynamics of a water balance for ombrogenous peat growth, thus clarifying the significance of this slow surface discharge as a function of the spatial structures with their water surplus situation. In this water balance we can distinguish the precipitation (P) that feeds the system, the evaporation (E), the vertical discharge or infiltration (Dv) and the horizontal discharge (Dh). The horizontal discharge has two aspects, the actual discharge of superfluous water and the 'system-linked discharge'. This system-linked discharge will be described in further detail here below.

In the northwestern European lowland plain, in which also the Bourtanger Moor is situated, the (former) raised bogs are present in regions where the mean annual rainfall is 700 mm or more (Streefkerk & Casparie 1989). In the locality of the study area the precipitation P nowadays has a mean value of 730–770 mm/year. The evaporation E from thriving *Sphagna* in an undisturbed raised bog (i.e. where there has been no interference by man) amounts to c. 550 mm/year (Burke 1975; Eggelsmann 1981). The vertical discharge Dv in living raised-bog systems is 25–40 mm/year (Eggelsmann 1960; Ivanov 1981; Streefkerk & Casparie 1987, 1989: Table 13; Streefkerk & Oosterlee 1984; Joosten & Bakker 1988). This would mean that raised bogs would be able to develop in the northwestern European lowland plain at a precipitation level of 550 + 40 (= E + Dv) = 590 mm/year. This is not the case. It is clear that the precipitation must be at least 110 mm/year more than the amount that disappears from the raised-bog system through evaporation and infiltration, assuming a mean annual precipitation of at least 700 mm. This extra requirement of 110 mm (P-E-Dv = 700–550–40 mm) involves (exclusively) surface discharge. This surface discharge is thus system-linked inasmuch as it maintains the water surplus situation. It is proposed that this slow discharge is required for the growth of peat-forming *Sphagna* and for the maintenance of the oligotrophic system. For this reason we refer to this kind of water discharge as system-linked or system-required discharge (Streefkerk & Casparie 1989). The spatial structures, discussed in 3.2.4.3., determine the pattern of this discharge.

In situations where the precipitation exceeds 700 mm, part of the horizontal discharge (Dh) can be regarded as genuinely superfluous water. With greater quantities of precipitation, as in the study area (730–770 mm), it may be assumed that more water is held in the peat deposit as a result of better conditions for peat formation. This may be expressed in more luxuriant peat growth with greater accumulation of organic material and also in the accumulation of fresh to poorly humified *Sphagnum* peat since 2000 BC. In addition, periods of water deficiency at the peat surface will be shorter and will occur less frequently.

3.2.6. *Discussion*

In the southern part of the Bourtanger Moor peat growth took place over a period of almost 13,000 years. Here the process came to an end only a few centuries ago as a result of the reclamation activities of man. The geological conditions in this upper course of the Hunze were evidently favourable for peat formation. Also the climatological development after the end of the Weichselian Glacial was favourable for the formation of extensive peat deposits in this valley. In fact this applies to the whole of the Bourtanger Moor (Fig. 8), which had a maximal size of c. 130,000 ha when the peat growth stopped as a result of artificial drainage. The size of the Bourtanger Moor is of the same order of magnitude as the enormous coastal mires which developed in the northwestern European lowland plain at the beginning of the Holocene, or slightly earlier, and which subsequently turned into raised bogs (Zagwijn 1986; Pons 1991, this volume, Ch. 2). There the process of peat formation – inasfar as data are available to us – followed broadly the same patterns as in the Bourtanger Moor. The similarities are not necessarily exact, as the geological situation and the hydrological regimes differed widely in the areas distinguished. Each raised bog has, as it were, its own specific characteristics as a result of many factors which jointly influenced the complex process of peat formation.

Peat research is a field of study of long standing, dating back to the first half of the 19th century. Although this field of research is constantly concerned with particular problems depending on the current views on peat formation held at any time, a vast quantity of information has nevertheless been acquired. The extensive inventories of the bogs in Lower Saxony (G.F.R.) made by Schneekloth & Schneider (1970, 1971, 1972) and by Schneekloth & Tüxen (1975, 1978), and the extensive standard work by Overbeck (1975) show that peat formation is a very general phenomenon in the northwestern European lowland plain, as has also been emphasized by many other authors (e.g. Pfadenhauer et al. 1980).

In this case study we have not intended to give a general overview of peat formation in the Netherlands and the surrounding countries. In this discussion we focus our attention on a few aspects of the peat stratigraphy in the study area. Comparison with other raised bogs is possible only on a limited scale, because the approach followed here, with much attention devoted to the mechanisms of peat formation, to the spatial structures and to the hydrology in an area extending over many square kilometres, has hardly been applied until now. Therefore no such comparison has been made here.

In this part of chapter 3 an attempt has been made to provide insight into the peat-growth mechanisms, and the development of soils and spatial structures of this large raised bog. How do the various elements of such a (raised) bog system relate to one another and how does such a system function? This description of the peat development is a broad outline. Many detailed data, notably concerning the vegetation development and the microscopic life in the peat, have necessarily been disregarded. Nevertheless the interrelation between various factors has become clearly evident. Such observed relationships are partly of a general nature, but are also partly very specific for the mire area under study. In this respect the following points can be mentioned:

1. The Late Glacial peat deposits appear to be primarily the result of the rise in temperature; as a consequence of this, water becomes available at the top of the permafrost soil and mire vegetation can establish. This is a very general phenomenon, and is not restricted to the area concerned.
2. The well-known transition from more eutrophic (fen) to oligotrophic, acidic (raised bog), peat-forming environments occurs also here. This process is regulated and influenced by many factors.
3. The geomorphological situation determined to a great extent the hydrological regime; this regime regulates the peat formation, sometimes even for thousands of years. A clear example of this is the Postwegrug (3.2.2.1., Fig. 8) with its overflow, which closely determined the drainage pattern.
4. In the course of thousands of years, hydrological regimes become established in which various types of peat accumulate. As this process continues, the hydrological systems become increasingly more wide-scale, culminating in the formation of purely ombrogenous peat.
5. The formation of raised bog is indeed possible within very broad climatic, geographical and temporal limits (see Ch. 2 and 3.1.3.1., 3.1.4.2.), but for ombrogenous peat formation to be maintained it is almost certain that very strictly determined spatial structures are required. These structures include the hummock-hollow systems, the bog pools, the domed complexes and contact zones, the 'Mooratmung', probably also the bog burst, and the permanent discharge of nutrients from the peat-forming environment.
6. The formation of raised bog peat is strictly limited to a situation of water surplus at the bog surface. In this connection Ingram (1983) distinguishes the hydrological concepts acrotelm and catotelm. To this can be added the concept of 'system-linked discharge' or 'system-required discharge' (Streefkerk & Casparie 1987). A living raised bog should receive more water in the form of precipitation than the amount of water that leaves the system through evaporation and infiltration. A superficial discharge is necessary in order to regulate a few acrotelm aspects and to maintain the catotelm conditions. This discharge, which is necessary as a source of feed for the peat-forming *Sphagna*, is probably at least 110 mm/year where the annual precipitation is at least 700 mm/year, the minimal amount for raised-bog formation in the northwestern European lowland plain.
7. Generally speaking, raised bogs are robust systems, which on the one hand react strongly to changes in the hydrological system, and on the other hand are able to survive rather wide fluctuations in precipitation, temperature, water quality, water level and drainage patterns, provided such fluctuations occur within a limited period of time so as to permit the recovery of the acrotelm conditions.

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