Changes in biotic conditions and metal deposition in the last millennium as reflected in ombrotrophic peat in Draved Mose, Denmark

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Surface samples of *Sphagnum magellanicum* and samples from peat columns in a profile from the raised bog Draved Mose, Denmark, have been studied to illuminate palaeobotanical changes and past and present deposition rates of metals. A *Sphagnum imbricatum* sociation dominated extended areas of the bog in the Middle Ages, whereas it is not found at present. The extinction of the sociation is closely related to the formation of hummock and hollow structures. In hollow areas the eradication was related to increased wetness while increased dryness caused the extinction on hummocks. Surface samples were separated into annual layers, and increment and dry matter production were calculated. The exposure of the *Sphagnum* patches to the prevailing wind direction has a considerable influence on increment rates and dry matter productivity. The possibility of using the metal-uptake in the annual peat layers as a recorder of the present deposition rate has been evaluated. Some trace metals and Mg seem to be sorbed and retained in quantities reflecting the present deposition level. Cs-137 and tritium-analyses have been used to elucidate the leaching process in the bog. Based on C-14 dates and the chemical composition of the peat columns, the mean annual storage of elements (A.D. 1300-1973) has been calculated. The relations between storage and past deposition rates are discussed.

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Knowledge about the present deposition of macro- and microelements has greatly increased due to a growing interest in their effects on man and his environment. While a number of different analytical methods are available for measuring the present deposition of elements, it is more difficult to obtain information about previous deposition levels. Only a few sources furnish such data; thus herbarium material of lichens collected back to A.D. 1882 has been analysed (Persson et al. 1974). Recently, peat bogs have attracted attention in this respect because they contain a huge amount of organic matter accumulated chronologically over decades. The ombrotrophic type of peat bog is especially suitable as precipitation and atmospheric dust provide the only sources of nutrient supply. Knowledge of the deposition mechanism and the movement of elements within deep peat deposits is still rather scarce (Damman 1978), and these informations are essential for determining the amount of chemical elements deposited in the past.

The chemical composition of peat has previously been studied from different points of view. Superficial peat samples have thus been analysed to determine the concentration of trace elements (Rühling and Tyler 1971; Tyler 1972; Pakarinen and Tolonen 1976a, 1976b; Sonesson 1973), Clymo (1965) studied the rate of organic matter loss in relation to water level and peat composition, and local vegetational changes related to the chemical environment during bog development were illuminated by e.g. Chapman (1964) and Tallis (1973).

The vertical distribution of trace elements in ombrotrophic bog profiles was studied by e.g. Tanskanen (1972), Sillanpää (1972), Pakarinen and Tolonen (1976), Lee and Tallis (1973) and Damman (1978). It was shown that some leaching or translocation takes place, but the leaching ability of the various elements seem to differ (Rühling and Tyler 1970). There are contradictory observations regarding the vertical distributions of e.g. lead in *Sphagnum* peat. A maximum in the surface layer was reported by Hvatum (1972) in Norway and by Sillanpää (1972) in Finland; whereas a distinct maximum deeper in the peat was found in southern Sweden (Tyler 1972) and in Finland (Tolonen 1974).

The washing out or removal of nutrients and microelements is reflected in the vegetational composition on the bog. Although the nutrient concentration is very low in ombrotrophic water, the increased water mobility in the channels draining ombrotrophic bog areas furnishes the necessary supply of nutrients to some minerotrophic plants. The more nutrient-demanding species thus only grow in the marginal parts of the bog areas (Malmer 1962; Sjörs 1963).

The aim of this paper is to present data on plant remains from peat deposited in the last millennium, to show ecological changes within this period, to estimate the present deposition of chemical elements and give the content of elements in peat at different levels below the surface, and from these data to discuss the mobility and accumulation of some of the elements.

Approach

The surface of the ombrotrophic peat bogs in Denmark is pillow-shaped, with the highest point lying in the centre. The bog accordingly does not interact with the minerogenic ground water from the surroundings, and all moisture is supplied from the atmosphere as rain or snow. The chemical elements are deposited with the precipitation or as dry fall-out. The elements are caught by the vegetation, and each year a new peat layer is formed which contains information about the environment. A peat profile thus provides a record of past changes.

The atmospheric input of elements was analysed in superficial samples of *Sphagnum magellanicum* and *Sphagnum cuspidatum*.

Information about past deposition levels was obtained from three vertical columns in a peat profile where relations between depth and age were calculated from a number of radiocarbon dates.

Past biotic and environmental changes were illuminated by peat stratigraphy, macrofossil analysis, and determination of humification degree.

Sampling site

Draved Mose is situated about 20 km from the North Sea in the southern part of Jutland (see fig. 1). The bog covers approximately 500 ha and is almost circular in shape. Most of the area has been disturbed by peat exploitation during the first part of this century. Only the central part of the bog (3.5 ha) is left in natural condition; the sampling site is located in this area at 19.5 m a.s.l. The undisturbed bog surface is flat with a distinct hummock-hollow structure (fig. 2). A few poorly growing *Betula pubescens* occur on hummocks. The mosaic structure disappears less than 50 m from the former peat excavation areas and is replaced by a uniform vegetation dominated by *Calluna vulgaris, Eriophorum vaginatum* and *Erica tetralix*. The surface slopes in this peripheral part due to artificial drainage

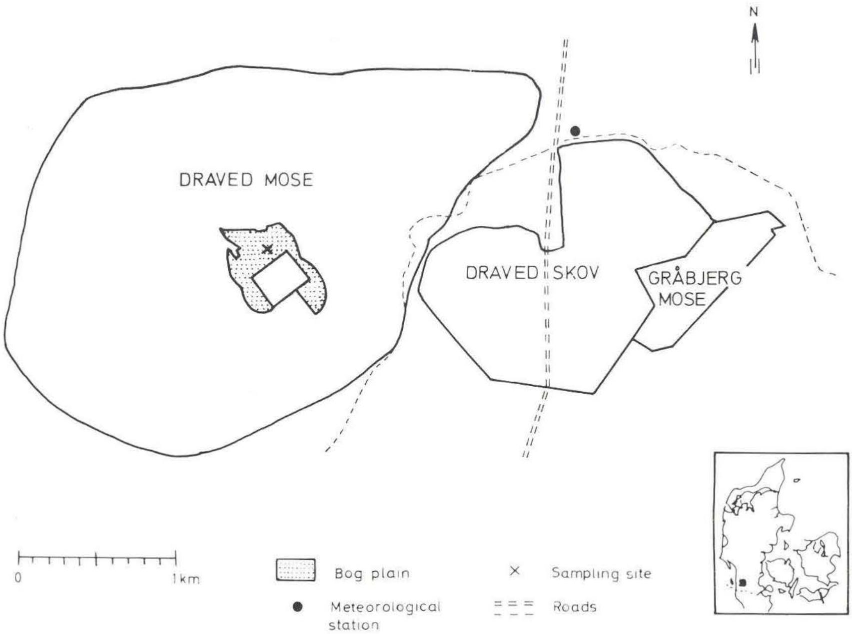

Fig. 1. Location map and the approximate size of the bog area shown in relation to Draved Skov and Gråbjerg Mose.

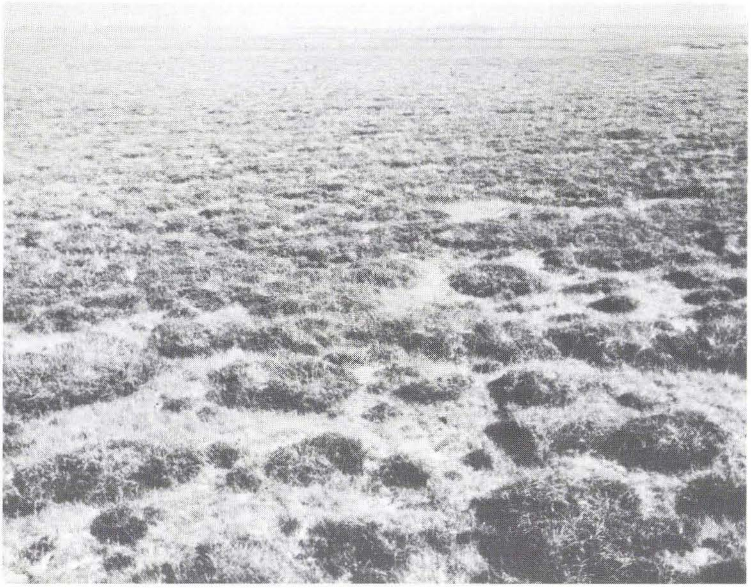

Fig. 2. The investigation area in the central part of the bog with a distinct pattern of hummocks (dark areas) and hollows (light areas).

from the neighbouring exploitation area. Only a few birch trees grow on the sloping parts of the bog plain.

The thickness of the peat in the central area is about 5 m. The formation of ombrotrophic peat began in late Atlantic time (Aaby and Tauber 1975) and ombrotrophic conditions have thus existed for more than 6000 years in this area. About 1 m of gyttja from an ancient lake is found below the peat. The bog is located on Saale till which is covered by aeolian sand blown up from the surrounding out-washed plains in late Weichselian time (Andersen 1966).

Meteorological data were measured at Draved just outside the bog; at Tønder, 10 km south of the bog; and at Askov, 50 km to the north. All the stations lie at approximately the same distance from the North Sea (table 1).

Vegetation at the sampling area

The hummocks were dominated by a *Calluna vulgaris – Eriophorum vaginatum* sociation whereas a *Rhynchospora alba – Sphagnum cuspidatum* sociation dominated the central part of the hollows. Close to the margin of the hollows a *Rhynchospora alba – Sphagnum cuspidatum* sociation with *Sphagnum tenellum* dominated. A *Sphagnum magellanicum – Calluna vulgaris* sociation was found in the marginal area of the hummocks.

Table 1. Yearly precipitation, and yearly temperatures. Mean values for the coldest and warmest months are shown in brackets.

Precipitation,	period	DRAVED	TØNDER	ASKOV
	1886-1925	–	750	733
	1931-1960	–	780	790
	1952-1977	837	803[1])	797[2])
Temperature,	period			
	1886-1925	–	7.6°C	7.2°C
			(0.4;15.8)°C	(-0.1;15.6)°C

1) Data from St. Jyndevad meteorological station.
2) Observation period 1957-1977.

A detailed description of the sociations found on the bog plain has been published by Hansen (1966).

Methods

Field work

Sampling from the bog surface

Superficial *Sphagnum* material was collected for analysis of the present input of chemical elements. In general only collections of two *Sphagnum* species were used to facilitate comparisons of data from different localities and from different years. *Sphagnum magellanicum* growing on hummocks was considered to represent the input to the hummock vegetation whereas *Sphagnum cuspidatum* was used for the hollow species.

The first sampling took place December 16, 1971, after the vegetative growth had stopped. The next sampling was in late winter (March) 1974 prior to the new vegetative period. The sampling was restricted to a rather small area (25 × 25 m) in the centre of the bog (fig. 1) and took place in periods of frost. This procedure definitely facilitated the accuracy of the field work and the later calculations.

Hummock sampling: A square of about 15 × 15 cm was cut out of the frozen *Sphagnum magellanicum* hummock and the area could easely be measured. The samples were placed in boxes to prevent secondary disturbance. The samples melted during transportation and were refrozen in the laboratory. The samples were separated in annual layers. To cut off a whole year's matter, some points are needed on the *Sphagnum* stem which can be referred to a relatively short growing period of the year. The most distinct point is the limit between material produced in late autumn (and winter, if mild) and that produced from the start of a new vegetative season in early April. Because of this fact the sampling in 1974 took place in March. The one-year period does not correspond to the calendar year but runs from April to April. For practical reasons, the period is named by the calendar year of the vegetative season.

Hollow sampling: Another procedure was used for *Sphagnum cuspidatum*. From investigation of the annual growth of *Sphagnum* from hollows (Overbeck and Happach 1957), it is known that in one year the stems may grow more than 12 cm. Only the capitulum and the uppermost part of the stem is erect, whereas the rest of the plant is weak and rests on the substrate. Thus a single plant does not have a fixed position from year to year but moves around in the hollow area. The slender stems were easily broken, and it was impossible to state the annual growth of single plants; accordingly no separation of annual production was possible. Instead, from 200 cm² a sample was taken which contained the capitula and a certain amount of dying or dead stem material. This fraction was named by the previous year. Below the first sample, another sample of *Sphagnum cuspidatum* peat was taken. Each of the samples had a thickness of 1.5 cm which was approximately the annual increment of *Sphagnum cuspidatum* mats in Draved Mose (Hansen 1966).

Sampling from the profile

In September, 1973, an open profile was excavated in two hummocks and the intervening hollow in the same area where the surface samples were taken. Prior to the excavation, the distribution of hummock and hollow areas was examined in an area of 7 × 6 m around the sampling site (fig. 3). Peat stratigraphy was

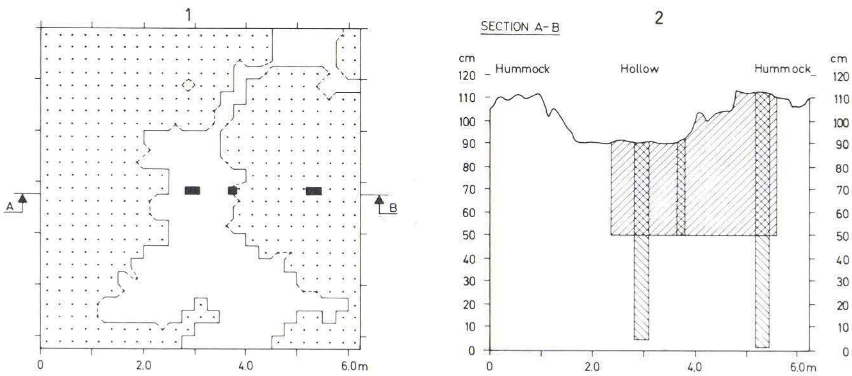

Fig. 3. Profile 1973: 1: The distribution of hummocks (dotted area) and hollows around the profile and the location of the peat columns (black area). 2: A vertical section of the profile showing the two hummocks and the intervening hollow. The three sampling sites are shown with parallel lines. Also part of the profile shown in fig. 4 is indicated by parallel lines, having another direction.

measured in the open section (fig. 4). pH and Eh profiles were measured in the hollow and the hummock peat by direct inserting of the respective electrodes, and continous series of samples 10 × 10 × 2 (or 3) cm were collected at three places: in the hollow, at the transition from the hollow to a hummock, and on the hummock (fig. 3). The peat slices were stored in polyethylene bags.

Laboratory work

The surface samples were dried immediately at 37-38^{0}C. The samples were ground prior to analysis.

The peat slices from the columns were divided into material for C-14 dating, for determination of humification degree, for analysis of ash content, and for chemical analysis. The material used for chemical research was dried at 37-38^{0}C whereas material used for other properties was dried at 80^0 for 2 days.

Macrofossil analysis

Three small subsamples were taken from each of the peat slices to show the general composition of the peat (plate 1). The untreated subsamples were mounted in glycerol jelly, and the *Sphagnum* stem leaves and branch leaves were determined to species or section. The results are given in an arbitrary scale because not every leaf or leaf-fragment could be identified with certainty. In addition, epidermis cells from *Ericales* and *Rhynchospora alba* were counted. *Eriophorum angustifolium* and *Eriophorum vaginatum* epidermis cells cannot be separated. Hence, the frequency of *Eriophorum* cells does not give any ecological information, and accordingly these data are omitted in plate 1.

Degree of humification

The method applied has been modified by Bahnson (1968) from the method developed by Overbeck (1947). It consists of a colorimetric determination of an alkaline extract of the peat. A description of the method in English has been published earlier (Aaby and Tauber 1975).

Ignition residue

The peat was ignited at 1000^{0}C. 550^{0}C data from similar peat types in a profile about 20 m to the west of the present investigation area (Aaby et al. 1979) show that the 1000^{0}C ignition residues are approximately 5% smaller than the 550^{0}C values.

Chemical analysis

Subsamples were digested in a mixture of HNO_3 and $HClO_4$, (4:1) and the metal analyses were carried out on the resulting wet ashing solution by atomic absorption spectrophotometry and flame emission (Perkin Elmer, Model 460, equipped with a HGA -74-graphite furnace). Na and K were measured by flame emission, Ca, Mg, Mn, Fe, Li, and Zn by flame absorption, and Cd, Cr, Cu, Ni, Pb, and V by graphite furnace absorption technique.

Interstitial water was pressed out of the surface samples and filtered through a 0.01 μm membrane filter by means of N_2-pressure. The resulting solutions were then acidified (0.15% HNO_3) and analysed according to the methods mentioned above.

The cation exchange capacity was determined on subsamples from the columns by a rapid method normally used in soil chemistry (Bascomb 1964). Some of the results were checked by the traditional NH_4Ac-method; no significant discrepancies were found.

The chemical data from hollows and hummocks are expressed in relation to dry weight of organic matter (DM) and, in addition, the hummock data are shown as annual net-uptake (mg m^{-2} y^{-1}).

Radiometric analysis

C-14: The measurements were made on samples dominated by *Sphagnum* material. Prior to analysis, the samples were boiled with 1% HCl and distilled water. The measurements were made by the C-14 laboratory of the Geological Survey of Denmark and the National Museum.

Cs-137: Freeze-dried bulk samples were analysed for Cs-137 by gamma ray spectrometry using germanium (lithium) detectors. To achieve the necessary sensitivity the samples were counted overnight. The measurements were made by The Danish Atomic Energy Commission, Risø.

Tritium: The wet bulk samples were treated at 2-5 atm. N_2 in a pressure membrane apparatus equipped with a 0.45 μm filter. The interstitial water thus obtained was distilled once to remove the yellow-brown humus colour. After distillation 8 ml were mixed with 12 ml scintillator (Instagel), and the tritium-content measured by liquidscintillation spectrometry on this mixture. The measurements were made by The Isotopic Centre, affiliated to the Academy of Technical Science.

The Cs-137 and tritium analyses were corrected for radioactive decay to the day of sampling.

Discription of peat columns

The deposits were described according to the system of Troels-Smith (1955). In addition, the degree of humification (H) is given in a 10 degree scale (v. Post 1924). The composition of the *Sphagnum* material is shown on the macrofossil diagrams (plate 1). The layer nos. refers to plate 1.

Hollow peat column

Layer no.	Level	
1.	0- 5 cm	Tangled, yellow *Sphagnum* peat with *Cyperaceae* remains. Tb^{1}3, Th^{1}1, T1^0+, D1^0+. *Rhynchospora alba* remains are frequent together with a few *Oxycoccus quadripetalus* and *Eriophorum angustifolium* (H2).
2.	5-11 cm	Tangled, light yellow *Sphagnum peat.* Tb^{0}4, T1^0+, Th^0+. *Rhynchospora alba, Oxycoccus quadripetalus* and *Andromeda polifolia* were present (H1).
3.	11-15 cm	Tangled, yellow *Sphagnum-Cyperaceae* peat. Tb^{0}4, T1^0+, Th^0+, D1+. *Eriophorum angustifolium* and *Rhynchospora alba* were rather frequent. (H2).
4.	15-18 cm	Yellow-grey *Sphagnum* peat. Similar to layer 3, but distinctly darker and not as tangled. Tb^{1}3, Th^{1}1, D1+. (H3).
5.	18-26 cm	Yellow *Sphagnum* peat. Tb^{0}4, T1^0+, Th^0+, D1+. The layer was similar to layer 2 but a little darker. (H2). Thin, darker bands were present (H3).
6.	26-55 cm	Brown *Sphagnum* peat. The upper limit was rather distinct. Tb^{2}4, T1^2+, Th^2+. *Oxycoccus quadripetalus* and *Calluna vulgaris* were found (H5).
7.	55-60 cm	Light brown *Sphagnum* peat Tb^{1}4, T1^1+,Th^1+, D1+. One *Andromeda polifolia* leaf was found. (H4).
8.	60- cm	Brown *Sphagnum* peat. Tb^{2}4, Tl^2+, D1+. Two *Eriophorum vaginatum* tussocks were present. (H5).

The macrofossil analyses (plate 1) and the peat stratigraphy (fig. 4) indicate that a *Sphagnum imbricatum* sociation has dominated the vegetation in this area for centuries. At about A.D. 1530 (see no. K 2290 in table 2) the *Sphagnum imbricatum* sociation was replaced by a *Sphagnum cuspidatum – Sphagnum tenellum* sociation. *Sphagnum tenellum* only dominated the vegetation for a brief period, and then it changed to a *Sphagnum cuspidatum – Rhynchospora alba* sociation, which is still found in the area.

The vegetational change about A.D. 1530 showed that a typical hollow was formed at that time and has persisted since then.

Hollow/hummock peat column

Layer no.	Level	
1.	Not indicated	Tangled, yellow, pale *Sphagnum* peat with *Cyperaceae* remains. $Tb^{0}3$, $Th^{0}1$, $Tl^{0}+$, *Rhynchospora alba* remains are frequent together with a few *Oxycoccus quadripetalus* stems. (H2).
2.		Tangled, yellow, pale *Sphagnum* peat. $Tb^{0}4$, $Tl^{0}+$, $Th^{0}+$. *Rhynchospora alba, Oxycoccus quadripetalus* and *Eriophorum angustifolium* were present. (H1-2).
3.		Yellow-greyish *Sphagnum* peat. $Tb^{1}3$, $Th^{1}1$, $Tl^{1}+$. *Rhynchospora alba* and *Eriophorum angustifolium* material were frequent. (H3).
4.		Dark chocolate brown *Calluna-Cyperaceae-Sphagnum* peat. $Tb^{3}1$, $Tl^{2}2$, $Th^{2}1$. *Eriophorum vaginatum* leaf basis and wood from *Calluna vulgaris* were frequent. (H6).
5.		Yellow *Sphagnum* peat containing *Cyperaceae* remains. $Tb^{1}4$, $Tl^{1}+$, $Th^{1}+$, Dl+. *Rhynchospora alba, Eriophorum vaginatum* and *Oxycoccus quadripetalus* were present (H2-3).
6.		Similar to layer no. 5 but with a darker colour. (H3).
7.		Light, yellow-brown *Sphagnum* peat. $Tb^{1}4$, $Tl^{1}+$, $Th^{1}+$, Dl+. *Rhynchospora alba* and *Andromeda polifolia* (one leaf) were present (H3).
8.		Brown *Sphagnum* peat. The upper limit is rather distinct. $Tb^{2}4$, $Tl^{2}+$, $Th^{2}+$. *Calluna vulgaris* and *Eriophorum vaginatum* were found. (H5).
9.		Similar to layer 8, but a little less tangled and a little darker (H5-6).

A *Sphagnum imbricatum* sociation dominated the deepest peat layer (no. 9 on plate 1). This vegetation was replaced by a *Sphagnum tenellum – Sphagnum cuspidatum* sociation (layer no. 7). *Sphagnum tenellum* dominated only for a short period after which a *Sphagnum cuspidatum – Rhynchospora alba* sociation with *Sphagnum tenellum* was found. Today *Sphagnum tenellum* developes on drier places in hollows, preferably close to the margins of hollows (Hansen 1966; Müller 1965). The rather permanent appearance of *Sphagnum tenellum* thus indicates that the marginal part of the hollow was drier than the central area where *Sphagnum tenellum* was rare. A *Sphagnum rubellum – Calluna vulgaris* sociation with *Eriophorum vaginatum* dominates layer no. 4 showing that a hummock had transgressed into the hollow area during a period of increased dryness on the bog surface. Although the *Sphagnum cuspidatum – Rhynchospora alba* sociation did not change in the hollow during the dry period, the lowered water table is reflected in the hollow peat as darker layers (layer nos. 3-4 in the hollow column) which is connected to the dark layer no. 4 in this column (fig. 4). Later, the humidity in the upper peat layers increased again (layer nos. 1-3), and the marginal area of the hummock became overgrown by a *Sphagnum cuspidatum – Rhynchospora alba* sociation with *Sphagnum tenellum*. This vegetation is still found on the locality. The center of the hummock thus seems to have had a rather stable location in time and only the marginal areas have transgressed or retreated depen-

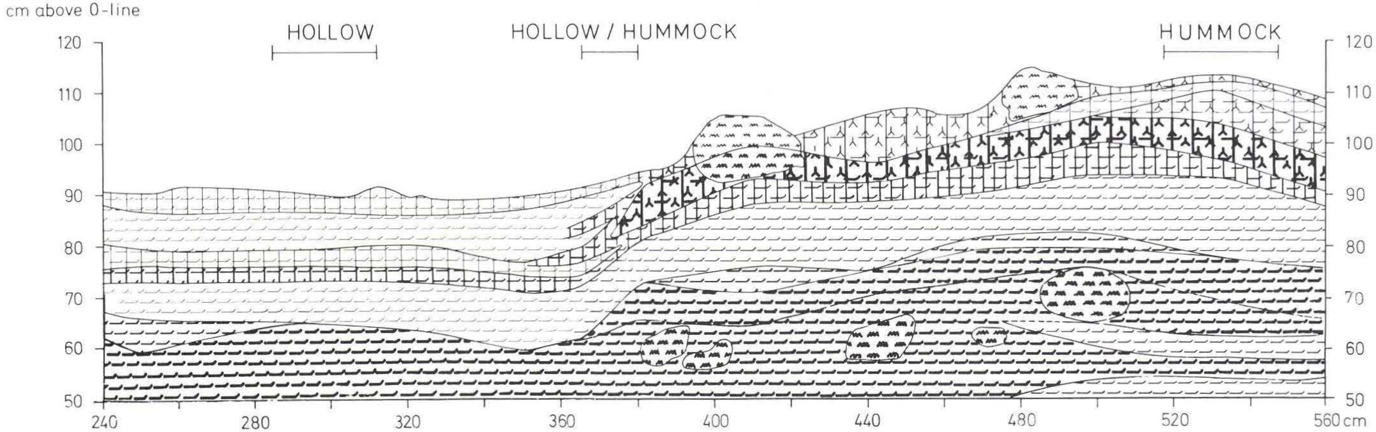

Fig. 4. Part of profile 1973 with peat stratigraphy and peat composition. The peat symbols are explained on plate 1. The degree of humification is shown by the thickness of the symbols. The composition of the symbols is in accordance with Troels-Smith (1955).

ding on the humidity in the upper peat layers. This result agrees with previous investigations on the bog (Hansen 1966; Aaby 1975).

Hummock peat column

Layer no.	Level	
1.	0-1.5 cm	Tangled, light brown *Calluna-Cyperaceae-Sphagnum* peat. Tb^{1}1, Tl^{1}2, Th^{1}1, D1+. Leaves from *Oxycoccus quadripetalus* and wood material from *Calluna vulgaris* and *Oxycoccus quadripetalus* were present together with *Eriophorum vaginatum* remains. (H3).
2.	1.5- 4 cm	Tangled, yellow, pale *Sphagnum* peat with *Cyperaceae* roots. Tb^{0}3, Th^{0}1, Tl+. The layer contained roots of *Eriophorum vaginatum* (H1).
3.	4- 8 cm	Light, yellow-brown *Sphagnum* peat containing roots from *Ericales* and *Cyperaceae*. Tb^{1}2, Tl^{1}1, Th^{1}1, D1+. *Oxycoccus quadripetalus* and *Calluna vulgaris* remains and *Eriophorum vaginatum* roots and leaves were present. (H3).
4.	8-16 cm	Chocolate brown *Calluna-Cyperaceae-Sphagnum* peat. Tb^{3}1, Tl^{2}2, Th^{2}1. *Calluna vulgaris* remains were frequent. (H6).
5.	16-20 cm	Light brown *Sphagnum-Cyperaceae* peat. Tb^{2}2, Th^{1}2, Tl^{1}+, D1+. Leaf basis and roots from *Eriophorum vaginatum* were frequent at some places. *Oxycoccus quadripetalus* leaves were found. (H4).
6.	20-31 cm	Yellow brown *Sphagnum* peat. Tb^{1}4, Tl^{1}+, Th^{1}+, D1+. Remains from *Oxycoccus quadripetalus, Calluna vulgaris* and *Eriophorum vaginatum* were found. (H3).
7.	31-33 cm	Light brown *Sphagnum* peat Tb^{1}4, Th^{1}+. *Eriophorum vaginatum* roots were present. (H4).
8.	33-40 cm	Chocolate brown *Sphagnum* peat. Tb^{2}4, Tl^{2}+, Th^{2}+, D1+. *Calluna vulgaris* and *Oxycoccus quadripetalus* wood were present. (H5).
9.	40-50 cm	Similar to layer no. 8 but a little darker. (H6).
10.	50-55 cm	Warm brown *Sphagnum* peat. Tb^{1}4, Th^{1}+. (H4).
11.	55-58 cm	Chocolate brown *Sphagnum* peat. Tb^{2}4, Tl^{2}+, Th^{2}+, D1+. *Calluna vulgaris* and *Andromeda polifolia* remains were found. (H6).
12.	58-63 cm	Similar to layer no. 10. (H4).
13.	63-76 cm	Similar to layer no. 11. A rather large *Eriophorum vaginatum* tussock was present. (H6).
14.	76-79 cm	Similar to layer no. 10. (H4).
15.	79-96 cm	Similar to layer no. 11. A rather large *Eriophorum vaginatum* tussock was present. (H6).
16.	96-106 cm	Similar to layer no. 10. (H4).
17.	106- cm	Similar to layer no. 11. (H6).

Earlier, a fairly homogenous *Sphagnum imbricatum* sociation dominated and *Sphagnum rubellum, Calluna vulgaris, Andromeda polifolia, Oxycoccus quadripetalus* and *Eriophorum vaginatum* had only a minor representation in the vegetation (layer nos. 5-17 on plate 1).

At about A.D. 1700 (see no. K 2286 on table 2) the vegetation changed distinctly. The open *Sphagnum imbricatum* 'Lawn' (Barber 1978) disappeared and was replaced by a *Calluna vulgaris – Eriophorum vaginatum* sociation. *Sphagnum rubellum* and *Sphagnum molle* became frequent later (layer no. 2 and 3).

The plant remains found in layer nos. 1-5 indicate that a typical hummock vegetation appeared about A.D. 1700 and has persisted in this area since then.

Calculation of time/depth scales of the hollow and hummock profiles

Four hummock samples and two hollow samples were radiocarbon dated in order to calculate time/depth scales (table 2). The dating results were calibrated relative to the American bristlecone pine chronology (Damon et al. 1973) in order to get approximate absolute ages for the samples.

The hummock time/depth scale (fig. 5) was calculated from the means of two successive dates; the youngest mean was calculated using the age 1973 for the

Table 2. Radiocarbon dates.

No.	level b.s.	C-14 date before year 1950	Calendar year A.D.
Hummock			
K2286	14- 16 cm	130 ± 100	
		230 ± 100	
	average	180 ± 100	1710 ± 108
K2287	46-48 cm	580 ± 100	1360 ± 104
K2288	73-76 cm	1020 ± 100	950 ± 105
K2289	106-109 cm	1150 ± 100	
		1260 ± 100	
		1380 ± 100	
		1230 ± 100	
	average	1260 ± 100	720 ± 102
Hollow			
K2290	24-26 cm	400 ± 100	
		380 ± 100	
	average	390 ± 100	1530 ± 113
K2753	63-66 cm	1140 ± 80	
		1140 ± 80	
	average	1140 ± 60	840 ± 69

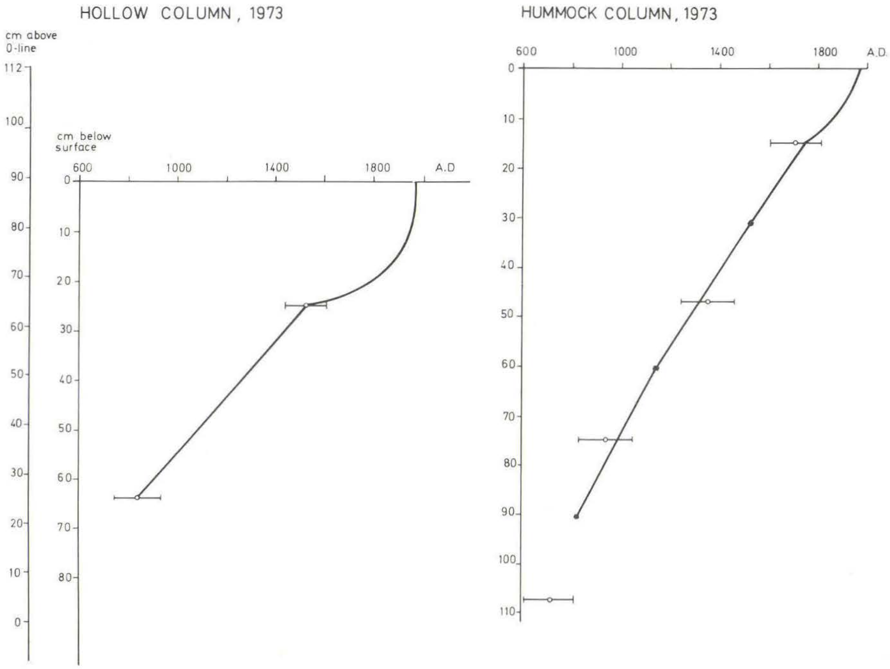

Fig. 5. Relations between age and depth in the hummock and hollow peat columns. The calibrated C-14 dates are shown as the mean value ± estimated standard deviation. The dots are mean values of two C-14 dates.

bog surface level. The mean ages apply to the mean level within the averaged interval. This procedure was used to reduce the statistical error on the individual C-14 dates. The straight lines connecting the mean values were used for dating the peat layers from 15-90.5 cm b.s. The dating of the topmost peat at 0-15 cm is somewhat uncertain. If the uppermost mean value is connected by a straight line to the 1973 level, the strongly humified *Calluna-Cyperaceae-Sphagnum* peat at 8-16 cm (see plate 1) will have a higher rate of accumulation than the upper, less decomposed layer at 0-8 cm. This result is not in accordance with the knowledge about rates of peat formation in young peat layers (Aaby and Tauber 1975; Aaby et al. 1979; Florschütz 1957; Nilsson 1964). Instead, an arbitrary curve was drawn between the 1973 level and the straight line at 15 cm. By using this curve for calculating the time/depth relations, the dark layer at 8-16 cm will show a lower growth rate than the lighter peat lying above and below (see table 3).

The hollow time/depth scale was calculated in another way because only two levels were C-14 dated. The mean rate of peat formation below 25 cm is calculated directly from the calibrated dates (table 2), whereas the ages of the upper peat layers are estimated based on increment rates from an adjacent profile with a

Table 3. Rates of peat accumulation. The calculation methods are explained in the text.

Hollow Depht	mm y^{-1}	Hummock Depht	mm y^{-1}
0- 5 cm	6.25	0- 5 cm	0.83
5-10 cm	2.77	5-10 cm	0.72
10-15 cm	0.77	10-15 cm	0.50
15-20 cm	0.44	15-31 cm	0.77
20-25 cm	0.21	31-61 cm	0.80
25-64.5 cm	0.57	61-90.5 cm	0.92

similar peat composition (Aaby et al. 1979). This scale was used without changes in the 1973 profile to date the upper 25 cm because the layer 25 cm below the surface (dated to A.D. 1530) has the same age in the two profiles. Calculated peat accumulation rates are shown in table 3. Accumulation rates in the hollow increase from 0.57 to 6.25 mm y^{-1}; the hummock rates are nearly constant.

Yearly productivity and increment rates of *Sphagnum magellanicum* collected from the bog surface

Eleven samples were collected from 5 hummocks.

Sample no. 1 was collected from hummock no. 1. The hummock was rather small, and the sample was located in a rather low, open area with a horizontal surface. *Sphagnum rubellum* dominated with a few *Calluna vulgaris*.

Sample no. 2 was taken from hummock no. 2. This hummock was larger than hummock no. 1, and the sample was located in a rather sheltered, open *Sphagnum magellanicum* vegetation which had a horizontal surface. *Sphagnum magellanicum* dominated with a few *Calluna vulgaris*.

Sample nos. 3-7 were taken from a large hummock (no. 3). The samples were all lying in an open *Sphagnum magellanicum* vegetation on the northern slope of the hummock approx. 10-15 cm above the hollow level. The *Sphagnum* vegetation was somewhat sheltered from westerly winds by *Calluna vulgaris* plants. *Sphagnum magellanicum* dominated with a few *Oxycoccus quadripetalus*.

Sample nos. 8 and 9 were taken from a large hummock (no. 4). They were not sheltered, and the surface was sloping to the north. The vertical distance to the hollow level was about 10-15 cm and *Sphagnum magellanicum* dominated.

Sample nos. 10 and 11 were located on a rather small hummock (no. 5). The samples were taken from the lower part of an open westsloping *Sphagnum magellanicum* vegetation with a few *Oxycoccus quadripetalus*. The samples were situated about 10-15 cm above the hollow level.

Four samples of *Sphagnum cuspidatum* were taken from 2 large hollows in 1974.

Each hummock sample could be separated into 2 sub-samples representing the organic matter produced in two successive vegetative seasons.

The dry matter production of *Sphagnum magellanicum* was calculated for the individual seasons (table 4). The productivity varies considerably from one hum-

Table 4. Annual dry matter productivity of *Sphagnum magellanicum* on raised bogs.

Draved mose, hummock	no. 3,	1973	: 906 gm^{-2}	(37°C)	(n = 5)
	no. 4,	–	: 730 gm^{-2}	–	(n = 2)
	no. 5,	–	: 645 gm^{-2}	–	(n = 2)
	no. 3,	1972	: 578 gm^{-2}	–	(n = 5)
	no. 4,	–	: 535 gm^{-2}	–	(n = 2)
	no. 5,	–	: 530 gm^{-2}	–	(n = 2)

Kaltenhofer Moor, Germany (Overbeck and Happach, 1957) 252-347 gm^{-2} (20°C)
Peat bog in Rhön, Germany (Overbeck and Happach, 1957) 374-662 gm^{-2} (105°C)
Peat bog in Rhön, Germany (Overbeck and Happach, 1957) 449-794 gm^{-2} (105°C)
Traneröds Mosse, Sweden (Damman, 1978) 104 gm^{-2} (37°C)
Russian bogs (Grebenschdschikowa in Overbech and Happach, 1957) 200-270 gm^{-2}

mock to another. High values were found on hummock no. 3, with samples which had been sheltered a little from the dominating west winds. The location on the northern slope of the hummock, rather close to the hollow, protects the *Sphagnum* vegetation from desiccation in drier periods during the growing season; these conditions cause a vigorous peat production. The dry matter production is lower from samples on hummock no. 4 which also was sloping to the north but not sheltered from westerly winds. The sample site facing westwards (no. 5) has the smallest calculated productivity. Because all of the samples were situated at about the same vertical distance to the water level, the distance from the water level cannot account for the different productivity on the three hummocks. The exposure of the *Sphagnum* mats thus seems to have a considerable influence on the dry matter productivity in windy areas.

The values for 1972 are 31% lower than the 1973 values; this difference can partly be explained by weaker growth in 1972 due to lower precipitation (750 mm in 1972, 1023 mm in 1973, cf. Hansen 1969; Overbeck and Happach 1957), partly by stronger decomposition of the 1972 material and partly by the fact that the *Sphagnum* capitulum has a relatively higher dry matter content than the rest of the plant material (Clymo 1965). The data from Draved Mose were compared with data from other ombrotrophic bogs (table 4); the annual productivity varies markedly within each locality and from one bog to another. Temperature, precipitation, lenght of vegetative season, and wind conditions are parameters which may influence the annual dry matter productivity. The very low productivity on Traneröds Mosse may have been somewhat below average due to a dry spring, according to Damman (1978). The German and Russian bogs have smaller production values than found on Draved Mose. Greater oceanity in the Draved Mose area may account for this difference.

The average increment of *Sphagnum magellanicum* mats in two vegetative

Table 5. Mean annual increment of ***Sphagnum magellanicum*** mats on ombrotropich bogs. The Draved mose 1973 and 1972 data are based on a period extending from April to April.

Draved mose, Denmark	1973	1972	1972/1973
Hummock no. 3	22.4 mm (n = 5)	19.4 mm (n = 5)	0.87
no. 4	21.6 mm (n = 2)	18.9 mm (n = 2)	0.88
no. 5	19.4 mm (n = 2)	17.8 mm (n = 2)	0.92
no. 3-5, mean	21.6 mm (n = 9)	19.0 mm (n = 9)	0.88
Precipitation	1023.2 mm	750.1 mm	
Draved mose, Denmark (Hansen 1966)			15.2 mm, mean of 3 years
Traneröds Mosse, Sweden (Damman 1978)			7.8 mm, one year
Peat bog in Rhön, Germany (Overbech and Happach 1957)			35 mm, one year
Peat bog in Rhön, Germany (Overbech and Happach 1957)			51 mm, one year

seasons was calculated by measuring the vertical distance between fixed levels on 20 frozen *Sphagnum* stems from 9 samples (table 5). The stems were taken at random in the margin of the sample, and only stems which showed two distinct levels of growth retardation were measured. Prior to calculations the measuring data were multiplied by 0.97 to give the length of unfrozen stems. The measured stems were somewhat crooked, especially in the lower part. The compression was mainly caused by the weight of the snow, and this effect influenced the increment data because only the vertical distance between the fixed points already mentioned (p. 9) was measured.

The annual increment varied from sample to sample within the same hummock and from one hummock to another. The mean increment for all samples was 21.6 mm ($\pm$ 2.18, n=9) in 1973 (table 5). The highest values were found in hummock no. 3 with sheltered samples on the northward sloping margin of the hummock. These samples also showed the highest annual dry matter productivity. The samples from hummock no. 4 were growing a little slower, and the smallest increment was found for hummock no. 5, which also had the smallest annual dry matter production. Exposure thus influences both the annual production of organic matter and the vertical growth of the *Sphagnum magellanicum* mats.

The average increment in 1972 was 19.0 mm ($\pm$ 1.33, n=9). The observed relations between the three hummock increments were identical with the 1973 relations. The 1972 data were generally 12% smaller than the 1973 data. The annual increment of *Sphagnum* mats is influenced by the precipitation (Hansen 1966; Overbeck and Happach 1957) which may account for a part of the differences between the 1972 and 1973 data.

When compared to other data (table 5), it is seen that the present data are in agreement with indirect measurements of *Sphagnum magellanicum* increments on the same bog in 1954-1956 (Hansen 1966). A much lower increment was

Table 6. Concentration of selected elements in the surface layers of 5 hummocks and 2 hollows in 1970, 1971, 1972 and 1973. Mean values in mg (kg DM)$^{-1}$.

Location	Element	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	V	Zn
Hummock 1 (n = 1)	70	1370	1.1	6.4	8.7	1630	3500	-	710	67	770	4.8	47	-	70
	71	1680	0.9	4.9	7.3	750	4400	-	860	116	840	4.1	-	-	57
Hummock 2 (n = 1)	70	1600	1.0	6.4	7.1	1310	3400	-	805	95	700	4.7	47	-	50
	71	1930	0.9	4.3	7.3	1040	3100	-	1130	98	950	4.3	50	-	57
Hummock 3 (n = 5)	72	2500	1.6	3.3	5.9	1200	2300	0.68	740	130	2000	2.3	53	8.2	63
	73	4400	1.4	2.5	5.1	900	3100	0.58	1200	200	1900	1.9	53	7.4	69
Hummock 4 (n = 2)	72	4100	1.7	3.6	6.2	1800	3000	0.90	700	82	2100	2.6	64	10	58
	73	2600	1.4	2.3	4.6	1000	3800	0.50	1300	130	2600	2.4	53	8.0	54
Hummock 5 (n = 2)	72	2700	1.7	3.6	6.6	1400	2700	0.80	1000	73	2100	2.3	50	8.5	63
	73	2200	1.7	2.1	4.1	800	3700	0.60	1200	110	2800	2.2	43	6.3	48
Hollow 1 (n = 2)	72	1200	2.2	3.1	6.6	2700	1700	0.90	1200	73	2300	2.5	176	9.0	99
	73	2100	1.2	1.8	4.2	1100	4300	0.50	1400	43	2400	2.4	112	8.0	73
Hollow 2 (n = 2)	72	1600	2.0	2.9	6.9	2500	1700	0.70	1200	78	1300	2.9	124	9.5	130
	73	1500	0.8	2.2	4.7	1400	3800	0.60	1300	69	1700	2.7	82	6.3	72

found by Damman (1978) on Traneröds Mosse, in southwestern Sweden, whereas the results from a number of German bogs show a higher annual increment. Some of the differences between the data from the latter bogs and Draved Mose may be due to different methods of measuring the increment. The German data show the total length of the plant which is not the case for the Draved data.

Metal elements in the surface layers

The chemical composition of the surface layers is summarized in table 6. Although the variation is marked, the concentrations of each element are within the same order of magnitude.

Hummock 1 and 2 are dominated by *Sphagnum rubellum* and *Sphagnum magellanicum* sociations, respectively. The concentrations of elements in the two sociations in 1970 and 1971 were compared to test if the chemical data are dependent on different *Sphagnum* material (table 7). The comparison shows no significant difference between the samples. This is in accordance with other findings (e.g. Rühling and Tyler 1971). All the samples from hummock 3,4, and 5 consist of *Sphagnum magellanicum*, and although they were exposed differently (see p. 19), the concentration values are nearly the same (table 7). In addition it is shown that samples from hollows have similar concentration values in each of the years, 1972 and 1973 (table 7). A homogeneity of metal concentrations in samp-

Table 7. t-test (paired observations) on the differences between the concentration values of metals in hummock and hollow samples from the years 1970, 1971, 1972 and 1973. It is presupposed that there is no significant difference between the per cent deviations of metals giving high and of metals giving small concentration values. This relation is tested for the linear least-squares fit. DF = Degrees of freedom.

Samples			Linear regression P	Difference P(t)	DF
Hummock	1 - 2,	1970	0.001 ***	0.73	11
–	1 - 2,	1971	0.001***	0.79	10
–	3 - 4,	1972	0.001***	0.12	13
–	3 - 5,	–	0.001***	0.05	13
–	4 - 5,	–	0.001***	0.24	13
–	3 - 4,	1973	0.001***	0.90	13
–	3 - 5,	–	0.001***	0.72	13
–	4 - 5,	–	0.001***	0.22	13
Hollow	1 - 2,	1972	0.001***	0.48	13
–	1 - 2,	1973	0.001***	0.15	13

les from hummocks and hollow, respectively, is thus shown for the years 1970, 1971, 1972 and 1973.

The mean concentration of selected elements in samples from hummocks and hollows was calculated for 1972 and 1973. A comparison of the hummock and hollow data shows that the mean concentration of Fe, Pb and Zn is highest in the hollows in the years 1972 and 1973, whereas the concentration of Ca is highest on the hummocks in the same years (table 8).

The concentration of chemical elements in hummock 3, 4, and 5 was converted to element net-uptake, defined as amount of metal present in the annual layers at the time of sampling (table 9). For immobile elements net-uptake equals deposition. Comparisons of the net-uptake data in 1972 and 1973 show that the values are nearly the same (table 10). A homogeneity of net-uptake values is thus indicated.

The homogeneity of the 1972 and 1973 metal data based on concentration values and net-uptake values was tested using a variance ratio-test (table 11). The differences between the 1972 and 1973 values were highly dependent on the method of comparison. The difference in concentration is for some elements contradictory to the difference in net-uptake. Due to the possibility of translacation the net-uptake might not reflect the true deposition but comparisons between samples based on net-uptake are superior to comparisons bases on con-

Table 8. Homogeneity of selected metal concentration means from hummocks (n = 8) and hollows (n = 4) for the years 1972 and 1973. A variance ratio-test was used.

I.	Hummock values > hollow values in 1972 and 1973.
II.	Hollow values > hummock values in 1972 and 1973.
III.	Hummock values > hollow values in 1973.
IV.	Hollow values > hummock values in 1972.

	Metals	Hom. 1972 P	Hom 1973 P
I	Ca	0.02 *	0.04*
II	Fe	< 0.001***	0.01*
	Pb	0.002**	< 0.001***
	Zn	< 0.001***	0.01*
III	Cd	0.07	0.01*
	Mn	0.10	0.009**
IV	K	0.005**	0.17
	Mg	0.002**	0.13

Cr, Cu, Li, Na, Ni and V showed no significant difference between the hummock and hollow values in 1972 and 1973 (P > 0.05).

Table 9. Net-uptake of selected elements in the surfase layers of 3 hummocks in 1972 and 1973. Mean values in mg $m^{-2}y^{-1}$.

Location	Element	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	V	Zn
Hummock 3 (n = 5)	72	1426	0.92	1.88	3.42	710	1350	0.39	420	73	1180	1.34	31	4.7	36
	73	4040	1.26	2.24	4.53	800	2800	0.54	1040	165	1720	1.70	47	6.7	63
Hummock 4 (n = 2)	72	2150	0.88	1.90	3.25	930	1600	0.48	380	44	1100	1.40	34	5.3	31
	73	1850	0.99	1.65	3.30	700	2750	0.36	910	98	1850	1.75	38	5.8	39
Hummock 5 (n = 2)	72	1400	0.88	1.90	3.45	750	1400	0.40	520	38	1100	1.25	27	4.5	34
	73	1400	1.07	1.30	2.55	490	2350	0.35	760	69	1800	1.40	27	4.0	31

Table 10. t-test (paired observations) on differences between the net-uptake values of metals in hummock samples from the years 1972 and 1973. It is presupposed that there is no significant difference between the per cent deviations of metals giving high and of metals giving small net-uptake values. This relation is tested for the linear least-squares fit. DF = Degrees of freedom.

Samples			Linear regression P	Difference P(t)	DF
Hummock	3 – 4,	1972	< 0.001***	0.32	13
–	3 – 5,	–	< 0.001***	0.96	13
–	4 – 5,	–	< 0.001***	0.32	13
–	3 – 4,	1973	< 0.001***	0.29	13
–	3 – 5,	–	< 0.001***	0.23	13
–	4 – 5,	–	< 0.001***	0.08	13

Table 11. Homogeneity of selected metal sample means on concentration and net-uptake from hummocks (n = 8) for the years 1972 and 1973. A variance ratio-test was used.

I. Elements with significantly higher 1973-level (concentration and net-uptake).

II. Elements with significantly higher 1972-level (concentration) but no significant difference in net-uptake.

III. Elements with no significant difference in concentration, but significantly higher 1973 level in net-uptake.

		Concentration $(mg(kgDM)^{-1})$	Net-uptake $(mg\ m^{-2}y^{-1})$
	K	0.002**	< 0.001***
I	Mg	< 0.001***	< 0.001***
	Mn	0.03*	0.01*
	Cr	< 0.001***	0.62
II	Fe	< 0.001***	0.24
	V	0.03*	0.09
	Cu	< 0.001***	0.51
	Ca	0.41	0.04*
III	Pb	0.26	0.02*
	Zn	0.32	0.03*
	Na	0.28	< 0.001***

Cd, Li, and Ni showed no significant differences (P > 0.05) Levels of significance, *P < 0.05, **P < 0.01, ***P < 0.001.

centration values because differences in yearly productivity are taken into account. Although the homogeneity of the concentration data is fulfilled, the comparison based on concentration values might lead to false conclusions as exemplified in the variance ratio-test (table 11).

Cs-137 and tritium-profiles

The Cs-137 profiles are presented in fig. 6. The concentration values, pCi $(gDM)^{-1}$ (pCi$\sim 10^{-12}$ Curie) show a gradual decrease as a function of depth whereas the deposition values, pCi cm^{-2} corrected for bulk density, show, in addition, a maximum in the interval 8-10 cm b.s.

The tritium profile is shown in fig. 7. In general the tritium content increases slightly with depth, and two maxima can be observed. The first maximum corresponds to a light layer (10-12 cm b.s.) just below the uppermost dark layer, and the second maximum (25-33 cm b.s.) is found just below the transitional zone where the degree of humification changes abruptly to higher values.

Distribution of elements in the peat columns

The chemical analyses of the peat columns are summarized in plates 2 and 3. To test the correlation of the individual elements in the profiles, factor analysis was performed using the layers as cases and the concentrations as variables (fig. 8). In both cases only two factors explain approx. 85% of the total variance, and the factor loadings for each element exceed + 0.5 or -0.5.

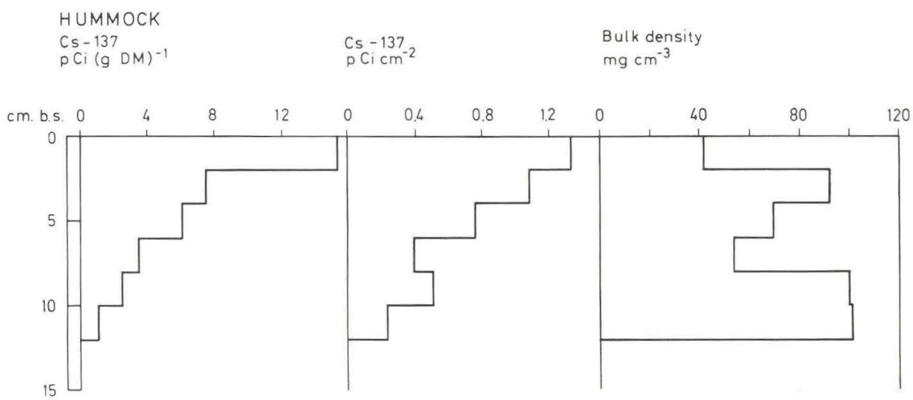

Fig. 6. The Cs-137 profiles shown as pCi$(gDM)^{-1}$ and pCi cm^{-2}. The bulk density values are used to calculate net-uptake values from concentration values.

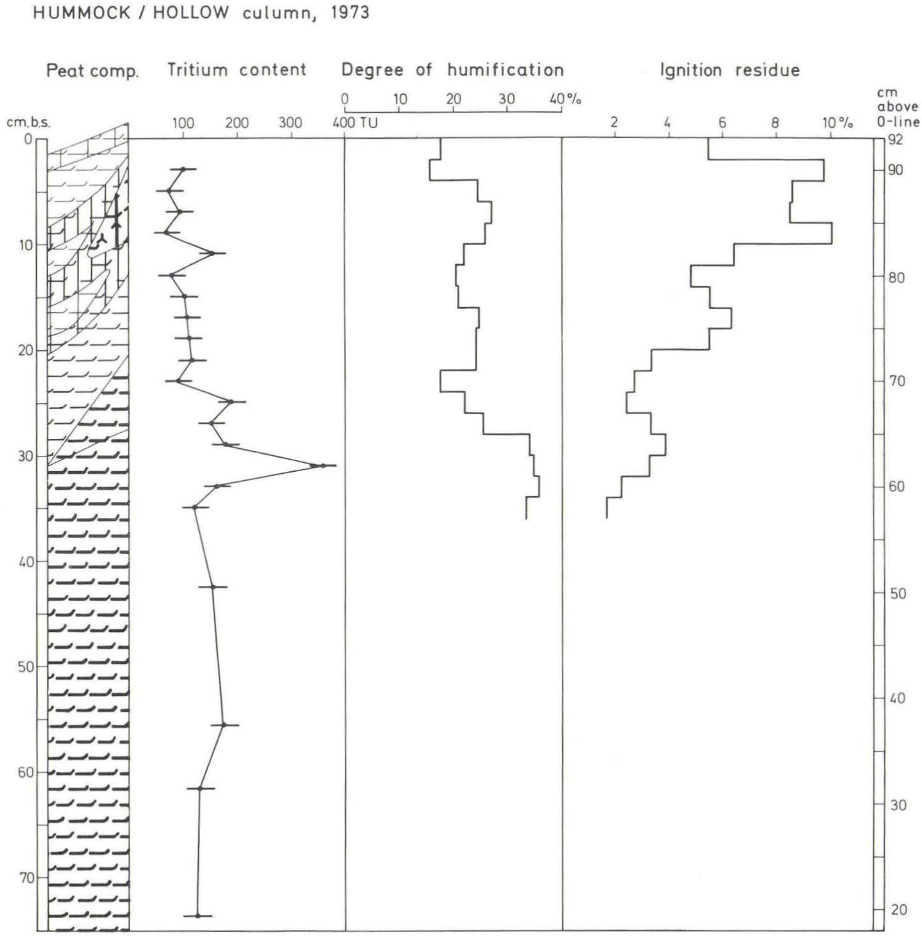

Fig. 7. The tritium profile with degree of humification and ignition residue.

The hollow column (plate 2)

Based on the factor analysis the elements are divided into three groups:

(1). The first group contains elements (high loading on factor 1), which are concentrated in the upper layers and show a distinct decrease with depth Cd, Cr, Cu, Fe, K, Li, Mn, Ni, Pb, V, and Zn. This decrease is especially pronounced for Fe and Mn which form a subgroup in the factor plot (fig. 8). K is positioned between this subgroup and the main group (the heavy metals) while Li is somewhat isolated, probably due to the broader maximum in the upper layers found for this element.

(2). The second group consists of Ca and Na (high loading on factor 2). The

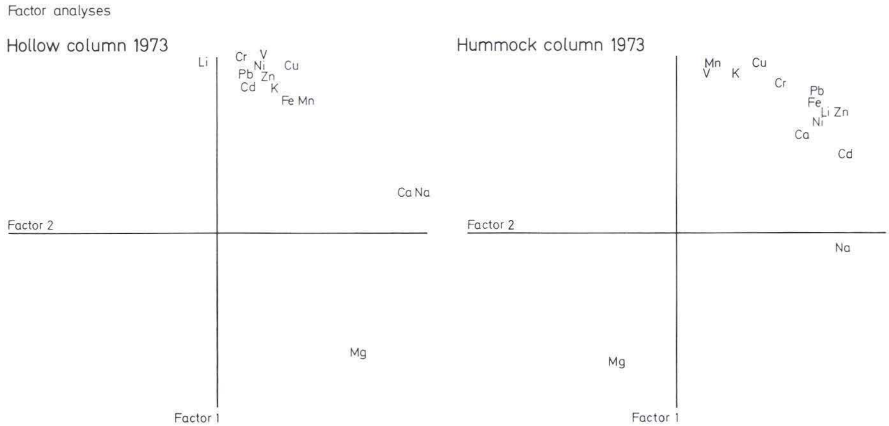

Fig. 8. Factor analyses plot. Method = Principal axes. Rotation = Varimax.

concentration of these elements does not change much with depth. A minimum is observed between 16 and 18 cm b.s.

(3). The behaviour of Mg is unique. The minimum found for Ca and Na is also present in the Mg-profile but the Mg concentration increases with depth (high negative loading on factor 1, see fig. 8).

As the ratio between the elements deposited cannot be assumed to have been constant during extended periods, the factor analysis may not solely reflect processes in the peat column.

The degree of humification shows two minima 4-10 cm b.s. and 17-26 cm b.s., indicating two permeable layers. The ignition residue shows marked variations in the upper 25 cm. Below this level it decreases to a nearly constant value of 1.5%. In the superficial segments of this profile a positive correlation between Fe and ignition residue is observed.

Eh decreases from approx. 200mV in the surface layer to approx. -50mV 15 cm b.s., corresponding to the position of the water level at the time of sampling. In the saturated zone the Eh increases to a value of approx. 50mV. The Eh profile confirms the importance af water logging.

pH increases with depth (4.0 to 4.6), the values being slightly lower than in the precipitation (~5.0).

The hummock column (plate 3)

Although the division of elements in groups is less distinct in the hummock, compared to the hollow, some similarities can be recognized (fig. 8):

(1). The heavy metals, K and Li are concentrated in the upper layers and decrease with depth. Some elements have a distinct maximum in the surface layer (e.g. Mn and K), for others (e.g. Pb and Zn) the concentration in the upper layers is nearly constant while Cd and Ni show a maximum below the surface level.

(2). As found in the hollow, the Na concentration is nearly constant, but the Ca concentration is markedly increased in the upper segment.

(3). For Mg the profile resembles the hollow profile

For all group 1 elements a distinct concentration minimum is observed in the layer 8-10 cm b.s., just above the strongly decomposed segment (10-16 cm b.s.). This minimum is probably caused by a shift in permeability making a nearly horizontal water transport dominating. Mg is concentrated in the layer (8-10 cm b.s.) indicating the importance of Mg in the leaching processes (ion-exchange).

A very pronounced change in concentration is observed in the segment 24-26 cm b.s., corresponding to the upper limit of the water level situated at the hollow surface. This change does not coincide with a sudden change in degree of humification or ignition residue, and thus it can only be explained as a hydrological effect.

As the content of dry matter does not change much in the segments 4-16 cm b.s. and 16-32 cm b.s. (unpublished data), a bulk density correction would not effect the trends.

Discussion

The extinction of *Sphagnum imbricatum* and the formation of hummock -hollow structures

The macrofossil analysis (plate 1) and the peat stratigraphy (fig. 4) indicated that a rather uniform *Sphagnum imbricatum* sociation dominated the bog plain in the Middle Ages. This sociation also had a widespread occurrence and abundance on raised bogs in the British Isles and Northwest Europe in the past (Green 1968; Overbeck and Schneider 1938). The *Sphagnum imbricatum* sociation is extremely rare in the same areas today, and is largely confined to hummock areas in very wet bogs. The rarity of *Sphagnum imbricatum* today is an enigma which has often been debated.

The extinction of the *Sphagnum imbricatum* sociation on Draved Mose is closely related to the formation of hummock and hollow structures. This formation was not a process which suddenly began in the 14th and 16th centuries, but was the result of changes in the surface topography which began about 500 years earlier. Radiocarbon dates show that the level 31 cm above the 0-line in the 1973 profile (fig.5) is contemporaneous in the hummock column and the hollow column. This level is dated to the 10th century and from that time the vertical difference between the two areas increases. Around A.D. 1300 the difference was about 10 cm in the profile, and when the *Sphagnum imbricatum* sociation disappeared in the hollow area at A.D. 1530, (K 2290 in table 2) the difference had reached about 15 cm. These values are calculated from the peat columns. The actual vertical differences in the past cannot be calculated because a number of processes (e.g. breakdown and autocompaction) may have influenced the differences. The humification values and the peat composition in the hummock area and the hollow area are nearly identical until A.D. 1530; hence the processes mentioned cannot have influenced the calculations seriously. During the period A.D. 1000-1500, the vertical differences between relatively low and high areas in the *Sphagnum imbricatum* sociation thus increased, and wetness in some areas reached a level which made *Sphagnum cuspidatum* and *Sphagnum tenellum* able to compete with *Sphagnum imbricatum* at only slightly increased wetness on the bog surface. A change in climate about A.D. 1500 caused increased wetness. The competition between *Sphagnum imbricatum* and the two other *Sphagna* seems to have lasted for a short time only and the best fitted species survived (see plate 1).

The ecological conditions still suited *Sphagnum imbricatum* on the drier places between the hollows. The bog surface relief continued to increase and the hummock area accordingly became drier, as reflected in the humification values (plate 3). About 200 years later, approx. A.D. 1710 (K 2286, table 2), the hummock area was too dry for *Sphagnum imbricatum* to be able to compete with the *Calluna vulgaris – Eriophorum vaginatum* sociation which then occupied the area and has dominated since that time.

The extinction of the *Sphagnum imbricatum* sociation and the formation of hummock-hollow structures is also illuminated in another profile which was excavated in 1978 and located only 20 m to the west of the 1973 profile (Aaby et al. 1979). The vegetational development in the hummock area and the hollow area in the 1978 profile was similar to that found in the 1973 profile except for two cases. (1) the hummock peat was generally formed at drier conditions than the hummock peat in the 1973 profile, and (2) *Sphagnum molle* was part of the sociation which replaced the *Sphagnum imbricatum* sociation in the hollow area. The disappearance of the *Sphagnum imbricatum* sociation from the hollow area in the 1978 profile was radiocarbon dated to about A.D. 1300. Unfortunately, the synchronous layer in the hummock area cannot be calculated at present, because only a single, younger C-14 date is available from this column. Of it is supposed that the relatively dry hummock area had an increment rate similar to the smallest rate found in the *Sphagnum imbricatum* peat in the 1973 profile (0.57 mm y^{-1}), the vertical difference between the hummock area and the hollow area has been approximately 9 cm about A.D. 1300. The vertical difference in the 1973 profile was calculated to 10 cm at the same time (fig. 5). It thus appears that the vertical differences in surface topography on the bog plain reached about 10 cm 650 years ago. This difference made the wetter parts of the *Sphagnum imbricatum* sociation sensitive to competition from a *Sphagnum cuspidatum – Sphagnum molle* sociation or a *Sphagnum cuspidatum – Sphagnum tenellum* sociation.

Only a small elevation of the water level would facilitate the growth of hollow sociations. Increased humidity is indicated by humification changes at about A.D. 1300 in the 1973 and the 1978 profiles. The *Sphagnum imbricatum* sociation persisted in the 1973 profile but disappeared from the 1978 profile. A new period of increased wetness on the bog surface began more than 200 years later, and at that time a hollow was formed in the 1973 profile, and *Sphagnum imbricatum* disappeared at this site.

The humidity on the surface of ombrotrophic bogs is strongly related to climate. Very little information about precipitation in the past is available, whereas more is known about temperatures. A temperature record has been constructed for England back to about A.D. 1100 (Lamb 1966). This record shows two periods with long-term trends towards lower mean annual temperatures. The first decrease began about A.D. 1250 and lasted for more than a century; the next decrease began about A.D. 1500 at the beginning of the so-called 'Little Ice Age'.

The meteorological data are thus in agreement with the results from Draved Mose because a lowering of the annual mean temperatures would affect the evaporation from the surface causing increased wetness on the bog.

In the hummock areas, the *Sphagnum imbricatum* disappeared at about A.D. 1600 in the 1978 profile (Aaby et al. 1979) and at about A.D. 1710 (K 2286 in table 2) in the 1973 profile, or 200-300 years later than in the respective hollow areas. Whereas the extinction of the *Sphagnum imbricatum* sociation in hollows on Draved Mose is closely related to changes in climate, the reasons for the disappearance of the sociation in the hummock areas is more obscure. It is difficult to ascertain whether the unfavorable drier condition was a result of periodically drier climate, or was a result of increased vertical differences between the hollow areas and the hummock areas.

The disappearance of *Sphagnum imbricatum* has been explained by terms of factors which altered the water regimes of the bogs toward increased dryness; either a change in climate (Godwin and Conway 1939; Hansen 1966), a change caused by man, e.g. drainage, burning and grazing (Jonas 1935; Pearsall 1956; Pigott and Pigott 1963), or autogenic bog processes (Morrison 1959). Green (1968) also thinks that a lowering of the water table was a main reason for leading to the present day restriction of the species, but other changes, e.g. a change in trophic status, might have been involved in its disappearance, according to Green (1968). Barber (1978) has shown that the extinction of the species at Bolton Fell Moss was climatically induced due to excessive wetness.

Some of the explanations mentioned above cannot be applied to the changes in

Draved Mose in a satisfactory way. First of all, the *Sphagnum imbricatum* sociation disappeared long before man influenced the bog environment. If man really was responsible for the extinction of *Sphagnum imbricatum*, it would be reasonable to suppose that the disappearance occurred simultaneously on the whole bog. This idea is contradicted by the fact that the extinction lasted for more than 400 years, A.D. 1300 - A.D. 1710. Moreover, there is no information indicating changes in trophic conditions, and there is no indication that a climatic change to greater dryness initiated the extinction. Instead, climatic changes caused increased wetness in restricted areas resulting in formations of hollows which were more fitted for other *Sphagnum* - sociations, as also shown by Barber (1978). Hence, only the disappearance of *Sphagnum imbricatum* in the hummock areas can be explained by increased dryness. Areas which were sufficiently wet for *Sphagnum imbricatum* may have persisted in the transitional zone between the hummocks and hollows. This area, however, seems to have been too restricted for the survival of a *Sphagnum imbricatum* sociation.

The possibility of using the surface layer, as a recorder of the present atmospheric input

Recently the atmospheric bulk precipitation of metals in different parts of Denmark has been determined (e.g. Jørgensen 1974; Hovmand 1977). By comparison with these results the usefulness of the surface layer as a recorder of the atmospheric input can be estimated (table 12).

By measuring bulk precipitation mainly wet deposition and part of the dry fall-out (particles > 10 μm) are determined whereas the deposition caused by absorption and impaction is underestimated. Consequently one expects the metal deposition on the bog to be somewhat higher than bulk precipitation. The metals can be divided into three groups (table 12):

(1) The deposition of Cd, Cu, Mg, Ni, Pb, V, and Zn is nearly the same in the two 'samplers'. The somewhat higher values found in the bog may be attributed to differences in the methods (see above).

(2) The amounts of Fe, K, Mn and to some extent Ca found in the surface layer of the bog are definitely higher than found for bulk precipitation.

(3) The Na content in the bog is destinctly lower than in the bulk precipitation.

In evaluating these results it must be stressed that the use of the net-uptake as a measure of the depostion is based on the following assumptions:

(a) The metals are sorbed quantitatively in *Sphagnum* tissue.

(b) The translocation of metals between the annual layers is negligible compared to the amounts present in the individual layers.

The sorption and retention of heavy metals in the bryophyte *Hylocomium splendens* examined by Rühling and Tyler (1970) are considered to be similar to

Table 12. Comparison of the metal deposition measured af net-uptake in the hummocks and in bulk precipitation.

Metals	Hummocks		Bulk precipitation	
	1972	1973	1972	1973
Ca	1600	3000	1040[1])	1360 [1])
Cd	0.90	1.17		0.5[2])
Cu	3.4	3.7		3.8[2])
Fe	760	710		180 [2])
K	1410	2700	240[1])	445 [1])
Mg	430	940	390[1])	895 [1])
Mn	59	130		9.1[2])
Na	1100	1800	3440[1])	8087 [1])
Ni	1.3	1.6		1.7[2])
Pb	31	41		21 [2])
V	4.8	5.9		3.7[2])
Zn	34	50		46 [2])

1) The values are interpolated, using data from St. Jyndevad, Højer (IHD 1977), and Draved meteorological station.
2) (Hovmand 1977)

that of *Sphagnum* sp. Based on the results of Rühling and Tyler (1970) it seems reasonable to assume that Cu, Pb, and Ni will be totally fixed in the peat under natural conditions. Although the mobility of Cd, V, Zn and especially Mg can be considerable, the similarity between the measurings in table 12 is striking. The fact that only negligible amounts of Cd, Zn, and V occur in the interstitial water (p. 12) also indicates that these metals are almost completely sorbed and retained by *Sphagnum*.

Fe and Mn are predominantly deposited as soil dust (Hovmand 1977) and consequently higher deposition levels in the bog should be expected for these elements (table 12), as part of the dry fallout is underrepresented in bulk precipitation. Dust deposition of Ca may also be important, as liming of the adjacent farmland is very intensive (table 12).

In addition to dust deposition another enrichment process seems to be active for Mn. Assuming that Fe is fully retained in the constantly aerated layers, the expected enrichment of Mn due to dry fall-out can be calculated from the Fe/Mn ratio in agricultural soils (Hovmand 1977). This calculation leads to distinctly lower Mn values than measured as net-uptake although the dust deposition has increased during the last century, judging from the ignition residue values (fig. 7; plates 2 and 3). Thus, a transport of Mn to the surface layers from below must take place. This result is supported by the distribution pattern of Mn in the peat columns (plates 2 and 3). The latter mechanism is without doubt also responsible for the extremely high net-uptake values found for the plant nutrient K (table 12), as reported by other authors (e.g. Damman 1978).

Na is obviously removed from the surface layers in large quantities (table 12) but the differences in Na supply in 1972 and 1973 seem to some extent to be recorded in the corresponding surface layers.

Leaching observations using Cs-137 and tritium as tracers

Significant levels of Cs-137 and tritium from test nuclear weapons have been detected in the atmosphere since the early fifties, with a maximum occurring in 1963 (Cambray et al. 1971; Andersen and Sevel 1974). Analyses of these tracers are used to illuminate the leaching processes in the bog.

Cs-137 has primarily been used as a dating tool in investigations of accumulation rates of sediment. The dating is based on the assumptions that Cs-137 is incorporated in the sediment in a distribution pattern similar to the one found in the bulk precipitation, that the mixing of the sediment is insignificant, and that no appreciable translocation will occur.

In the bog the first and the second assumptions are sustained, and thus the translocation of the univalent Cs-ion can be examined.

When the Cs-137 profiles (fig. 6) are compared to the estimated annual deposition corrected for radioactive decay (half-life 30 years) to the day of sampling (e.g. Pennington et al. 1973), the distribution pattern shows no resemblance. The content of the surface layers are higher than would be expected from precipitation measurings indicating an upward transport in the bog. On the other hand an appreciable amount is also found in layers produced before the year 1950. This can only be explained by leaching. In accordance with this only 4.2 pCi cm^{-2} of the original 14 pCi cm^{-2} deposited (Asker Årkrog, pers. commun.) are left in the uppermost 12 cm of the bog. The recycling and leaching indicated by the Cs-137 measurements are probably important for other cations also, especially those of similar electric potential.

The tritium content in the precipitation ($^3H_20$) shows a maximum of ca. 2000 TU (tritium unit) in 1963 expressed as annual mean (the seasonal variation is very pronounced with a maximum in the summer). Since then a gradual decrease in the concentration has taken place reaching about 100 TU in the year of sampling (1973) (Andersen and Sevel 1974). Consequently, TU values higher than 100 in the interstitial water can be taken as evidence for mixing with a certain amount of 'older' water, i.e. water from around 1963.

The tritium profile (fig. 7) shows that the content in the uppermost 10 cm equals the values expected from precipitation. The increase at 10-12 cm b.s. is believed to be due to mixing with 'older' water retained in the more impermeable (darker) layer placed above. The permeability is negatively correlated to the degree of humification (Malmström 1928). A change in permeability with degree of humification can also explain the maximum found at approximately 30 cm b.s. as 'older' water is slowly mixed with water precipitated in recent years. In the deeper parts of the hollow the tritium content is approx. 150 TU indicating that although 'old water' is stored here, infiltration of water precipitated after the year 1963 must have taken place. The tritium analyses cleary show that the correlation between permeability and degree of humification must be considered when the leaching patterns in the bog are to be evaluated.

The sorption capacity of the peat

Although the metal elements may be bound in different ways in the peat, ion exchange has been demonstrated to be very important (Puustjärvi 1955; Rühling and Tyler 1970). Consequently, changes in cation exchange capacity (C.E.C.) might explain part of the variation in the concentration profiles. Measurings of the C.E.C. (not published), however, showed no substantial variation with depth and no correlation with degree of humification. The C.E.C. varied from 1.2 to 1.4 meq(g DM)$^{-1}$ and exceeded in all the segments the sum of cations; the C.E C.-values resemble those reported by Tyler (1972).

Changes in deposition rates over extended periods

From the comparison of net-uptake and bulk precipitation discussed earlier (p. 34) it can be concluded that the elements Cd, Cu, Mg, Ni, Pb, V, and Zn are retained in the surface layer in quantities reflecting the actual deposition. Fe and Ca may behave similarly whereas Na, K, and Mn are translocated.

As the radiocarbon dates have made it possible to establish a time/depth scale in the peat columns, the mean annual storage in a given period can be calculated. The possibility of using the annual storage as a record of the actual deposition in the past will be discussed in the following with special emphasis on the group of elements retained in the surface layer. A further development of this approach has been reported by Aaby et al. (1979).

The deposition conditions in the hummock/hollow system

The development of the hummock/hollow system has been shown to take place about A.D. 1530 in this area. Since then the deposition conditions have been different on the hummocks and hollows partly because of the discrepancy in vegetation and microclimate and partly because of the different positions of the water table.

Although the trends in the chemical profiles (plates 2 and 3) are similar for the hummock and the hollow, the distribution of the elements differs somewhat. The most important difference is the high concentrations of most of the elements found within the upper zone of water fluctuations in the hummock, which certainly must be attributed to translocation. Among the factors governing this process the following mechanisms are believed to be important:

(1) During a heavy rainfall the infiltration af water might be so quick in the unsaturated zone that the reaction time needed for complete sorption exceeds the actual time of contact.

(2) Due to redox-processes some elements (e.g. Fe) concentrate in the zone of water fluctuation as in mineral soil.

(3) A transport of elements from the hollow into the hummock may appear especially during winter, when ice formation can facilitate such water movements.

Judging from this comparison of the hummock and the hollow, the latter is regarded as the most suitable recorder of the annual input, and although some horizontal movement of elements between the hummock and the hollow cannot be disregarded, it would still be a minor fraction compared to the total deposition.

Estimation of the relative importance of metal sources

Due to escalating industrial activity, transport activity, and energy production, the deposition of heavy metals has increased during the last centuries.

As reflected by the ignition residue and iron content of the peat columns (plates 2 and 3), the deposition of earth dust has increased with time. This is presumably a consequence of intensified mechanisation of the agriculture from the beginning of the 20th century. The chemical composition of the particles deposited on the bog can be estimated from chemical analyses of agricultural soil (Hovmand 1977). Assuming that Fe originates solely from earth dust, these analyses can be used to calculate the metal contribution in the dry fall-out (table 13).

Table 13. Estimation of the input of elements (mg m^{-2}) from different sources in 1972.

Element / Source	Cu	Pb	Cd	Ni	V	Zn	Fe	Mg
Soil dust	0.73	1.8	0.02	0.66	1.7	3.2	760*	140
Sea aerosoles	<0.01	<0.1	<0.01	<0.01	<0.1	<0.1	–	290
»Natural input«	0.73	1.8	0.02	0.66	1.7	3.2	760*	430*
Net-uptake in Hummocks	3.4	3.1	0.90	1.3	4.8	34	760	430
Antropogenous input in %	79	94	98	50	65	91	–	–

*Postulated values.

Another important source of elements is sea aerosols. Supposing that Mg arises from earth dust and sea aerosols only, the amounts of metals originating from the latter source can be estimated from the element ratio in sea water (Turekian 1969). Following this mode of procedure the total 'natural input' of Cu, Pb, Cd, Ni, V, and Vn in 1972 (a climatically rather 'normal' year) was calculated (table 13). It appears that the contribution to the 'natural input' from sea aerosols is negligible except for Mg.

The deposition originating from earth dust can only explain a minor fraction of the net-uptake, and consequently the 'antropogenous input' is dominating (table 13).

Trends in mean annual storage

The mean annual storage of Cd, Cu, Mg, Ni, Pb, V, and Zn in the hollow and the hummock columns have been calculated for the period A.D. 1300-1973. Due to the rather low accuracy of the C-14 dates, a time interval of 100 years was used (table 14). As previously mentioned, mean annual storage can only be expected as a meaningful measure of deposition rates in the hollow column, and in the hummock column prior to the development of the hummock/hollow structure, A.D. 1530.

The trend in the mean annual storage of the elements Cu, Pb, Ni, and V is in accordance with the expected depositional development. The values are almost constant in the period A.D. 1300-1700 and during the last three centuries a gradual increase is observed. As regards the absolute values, it appears that the storage level in the past is significantly lower than the present day 'natural input' (table 13). This discrepancy is presumably a consequence of additional deposition of soil dust due to the present activity of man.

In the segments dominated by an even *Sphagnum imbricatum* vegetation (prior to A.D. 1500) the storage levels in the hollow and the hummock columns are identical.

In most respects the behaviour of Cd is similar but the rather high storage values found in the period A.D. 1300-1700 may indicate that this element is translocated to some extent.

The storage values of Zn in the periods 1300-1400 and 1400-1500 (table 14) in the *Sphagnum imbricatum* dominated part of the hollow, and hummock columns are somewhat different; consequently the method may not be applicable for this element.

As the supply of Mg is dominated by the sea aerosole contribution, complete retention of this element would result in a rather constant storage level increasing slightly in the 20th century due to additional deposition of earth dust. The actual

Table 14. Mean annual storage (mg $m^{-2}y^{-1}$) of elements in hollow and hummock.

Element	Cu		Pb		Cd		Ni		V		Zn		Mg	
Period	Hol.	Hum.	Hol.	Hum.	Hol.	Hum.	Hol.	Hum.	Hol.	Hum.	Hol.	Hum.	Hol.	Hum.
1900-1973	1.36	2.70	14.5	16.4	0.19	0.46	0.34	0.55	0.89	1.11	11.2	31.0	127	182
1800-1900	0.46	0.53	7.4	7.5	0.13	0.17	0.15	0.15	0.34	0.17	4.0	8.9	112	148
1700-1800	0.13	0.33	2.4	5.2	0.06	0.15	0.09	0.12	0.15	0.09	1.8	9.0	57	124
1600-1700	0.07	0.27	1.2	4.2	0.04	0.19	0.04	0.12	0.08	0.10	1.2	8.7	45	155
1500-1600	0.08	0.09	1.3	1.0	0.04	0.07	0.04	0.08	0.07	0.09	1.7	3.0	76	155
1400-1500	0.09	0.09	1.3	0.8	0.06	0.05	0.06	0.04	0.07	0.04	2.1	0.4	136	167
1300-1400	0.06	0.07	1.1	0.8	0.05	0.04	0.05	0.04	0.05	0.03	1.4	0.1	144	126

values do not support this assumption. The absolute values are lower than would be expected from the net-uptake calculations in the surface layers (table 12). Furthermore the very low values found in the period A.D. 1500-1800 are in all probability referable to intensive leaching in the corresponding slightly humified and highly permeable layers.

Similar mean annual storage levels as those found in the present study have been measured on identical peat types from the same bog (Aaby et al. 1979, unpublished data).

Final remarks

This investigation emphasizes that knowledge of stratigraphy, peat composition, permeability (reflected by degree of humification), and increment is essential when the distribution of elements in a peat profile is to be interpreted. Conclusions, based on concentrations and contents only (Sillenpää 1972, Damman 1978), are thus considered to be ill-founded.

The study indicates that the annual storage of Cu, Ni, Pb, and V in the hollow column may be used as a recorder of changes in the deposition rate during extended periods.

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Dansk sammendrag

Overfladeprøver af *Sphagnum magellanicum* og prøver fra tørvesøjler i et åbent profil er undersøgt for at belyse tidligere vegetationsændringer og tungmetallers deponeringshastighed i fortid og nutid.

Ved hjælp af makrofossil analyse og C-14 datering vises at en *Sphagnum imbricatum* sociation har dækket store arealer på mosen i middelalderen, medens den i dag er helt forsvundet. Udryddelsen er tæt forbundet med dannelsen af tuer og høljer. I to perioder, omkring år 1300 og 1530 blev der dannet høljer på mosen og *Sphagnum imbricatum* sociationen blev afløst af en *Sphagnum cuspidatum* - *Rhynchospora alba* sociation. På de mellemliggende tuearealer vedblev *Sphagnum imbricatum* sociationen at dominere ca. 200-300 år længere end i de respektive højlearealer, hvorefter den også forsvandt her. Klimatiske ændringer til større fugtighed på mosen var således afgørende for sociationens undergang i høljeområderne. I tuearealerne er det derimod tiltagende udtørring af tørvelagene der betinger udryddelsen af *Sphagnum imbricatum;* men det er vanskeligt at fastslå, hvilke forhold der har været afgørende for denne udtørring. Forøget tørhed kan skyldes øget overfladerelief, d.v.s. større vertikal afstand mellem høljebund og tuetop, klimatisk ændring eller en kombination af disse forhold.

Overfladeprøver er blevet opdelt i årslag og der er målt højdetilvækst og tørstofproduktion. Det kan vises at vindeksponering har stor betydning for tilvæksthastighed og tørstofproduktion.

Ud fra kemiske analyser af overfladeprøver er det undersøgt, om indholdet af metaller i tørven afspejler det aktuelle metalnedfald. Det kan vises at forskellige prøver fra henholdsvis tue og hølje har omtrent samme metalindhold beregnet både som relativ (mg (kg DM) $^{-1}$) og absolut (mg $m^{-2}y^{-1}$) værdi. Kun de absolutte værdier bør anvendes som sammenligningsgrundlag for prøver, idet sammenligninger baseret på koncentrationsværdier kan lede til falske slutninger. Sammenligninger med målinger af metalnedfaldet opsamlet i en tragt (bulk-precipitation) synes at godtgøre, at de undersøgte spormetaller og Mg fixeres i det recente *Sphagnum* materiale.

Cs-137- og tritium-analyser er forsøgt anvendt til belysning af udvaskningsprocessen i mosen. Cs-137 er fordelt i tørveprofilet på en sådan måde at både udvaskning og transport opad i tørvesøjlen må have fundet sted. En lignende translokation må påregnes for de mere mobile elementer, f.eks. K og Mn.

Tritiumanalyserne viser, at infiltrationen af nedbøren primært foregår gennem de lyse, svagt humificerede lag.

Ved hjælp af C-14 dateringerne og den kemiske sammensætning af tørvesøjlerne er indholdet af metallerne Cd, Cu, Mg, Ni, V og Zn i de forskellige årslag beregnet (år 1300-1973). På grund af den relativt grove tidsskala er 100-års middelværdier anvendt.

Relationen mellem tørvens metalindhold og deponeringen gennem tiderne er diskuteret ud fra vurderinger af bidragene til deponeringen fra forskellige kilder (jordstøv, havaerosoler og antropogent materiale). Resultaterne tyder på, at indholdet af Cu, Ni, Pb og V i tørvelagene kan anvendes som et direkte mål for deponeringen helt tilbage til år 1300.

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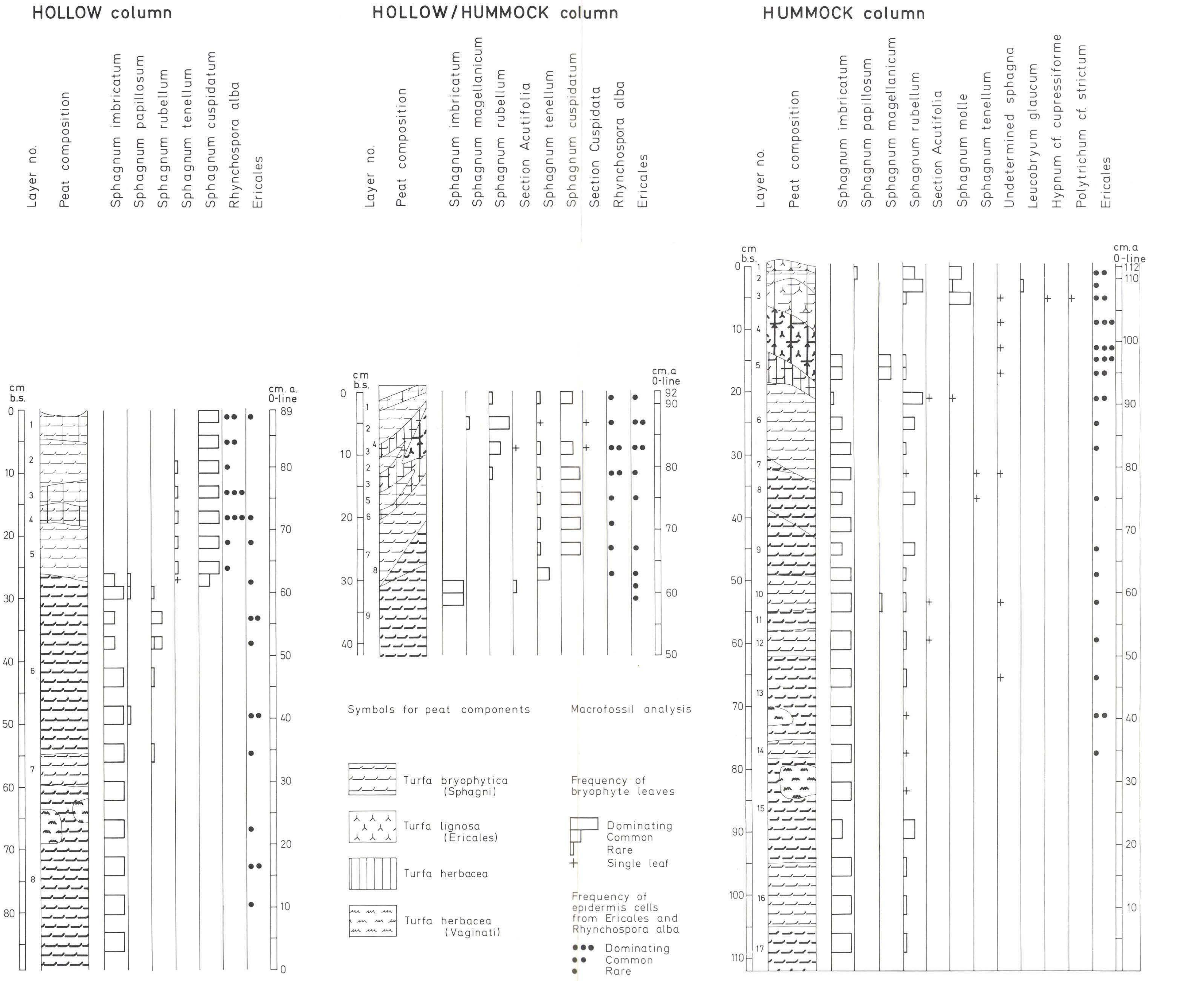

Plate I. Macrofossil diagrams.

DRAVED MOSE

HOLLOW COLUMN, 1973

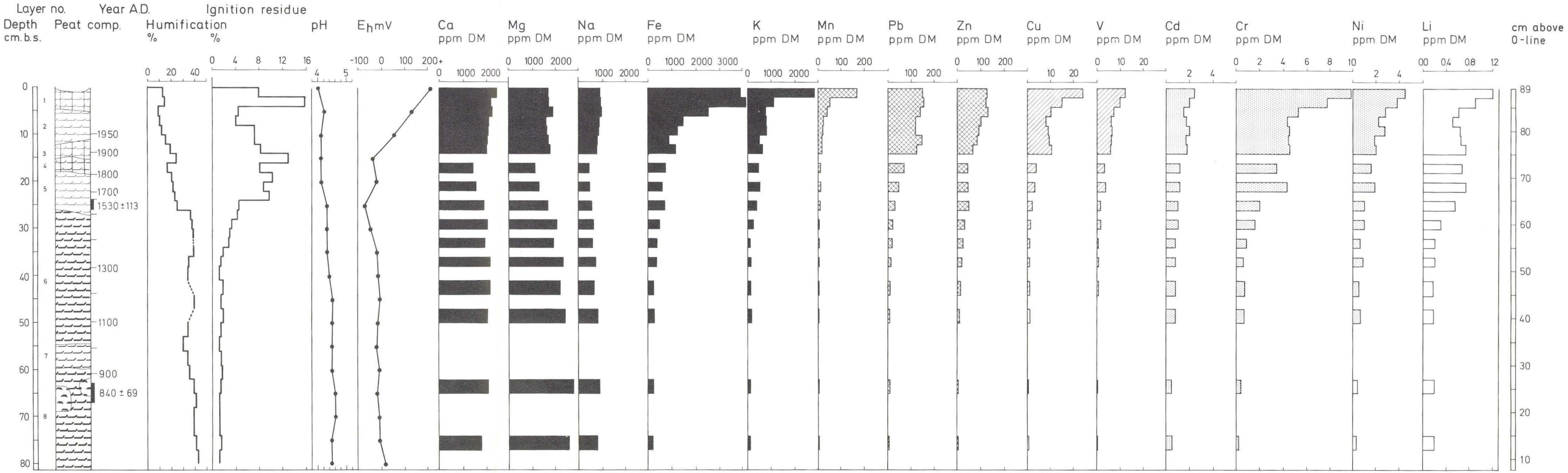

Plate 2. Hollow column, 1973. The peat composition symbols are shown in plate 1.

DRAVED MOSE
HUMMOCK COLUMN, 1973

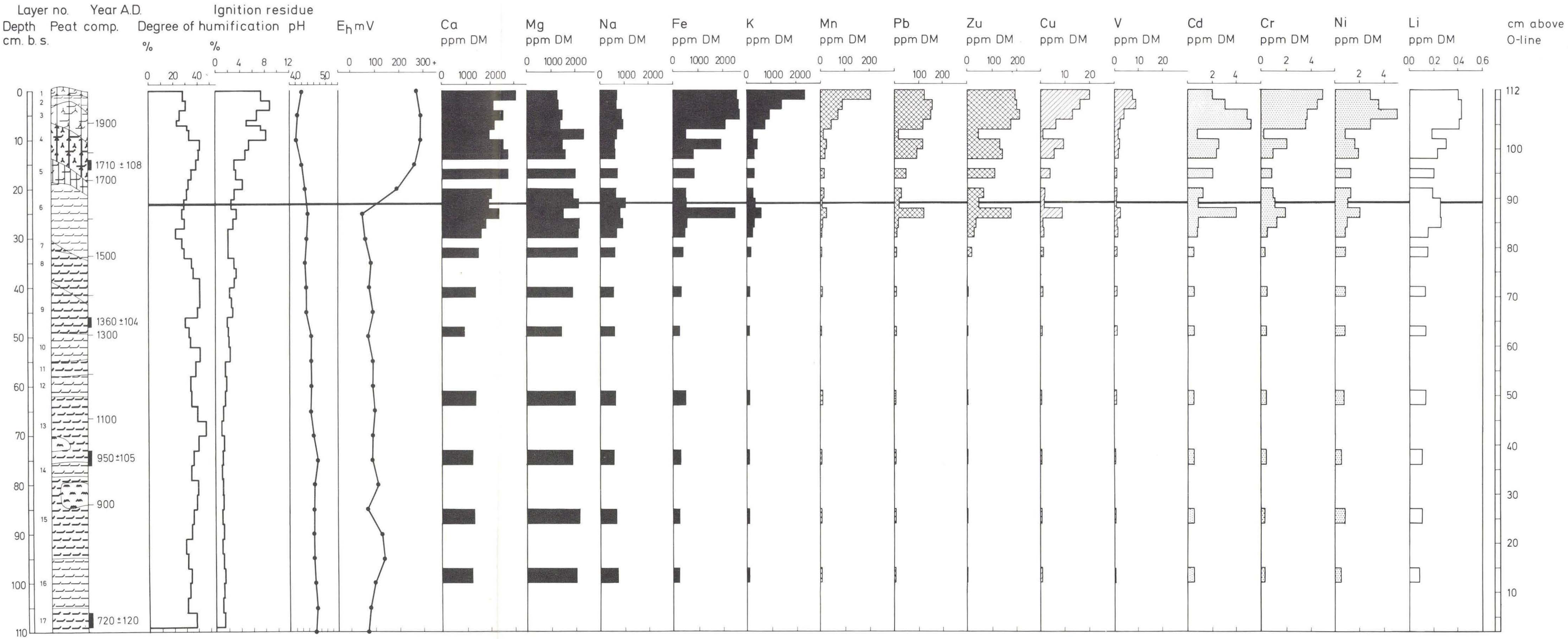

Plate 3. Hummock column, 1973. The peat composition symbols are shown in plate 1. The thick line at 23 cm below surface (b.s.) indicates the hollow column surface.