STRATIGRAPHIC AND PALEOCLIMATIC STUDIES OF A 5500-YEAR-OLD MOSS BANK ON ELEPHANT ISLAND, ANTARCTICA

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ABSTRACT
Analyses of a core from the deepest known moss peat bank in Antarctica, on Elephant Island, South Shetlands, show that this Chorisodontium aciphyllum-dominated bank began to grow ca. 5500 14C yr BP. Combined with other studies in the region the present study indicates more extensive glaciation before 5000 to 6000 BP than today on some of the South Shetland Islands. The main hypothesis is that these frozen moss banks contain important paleoclimatic information. The stratigraphic parameters analyzed included degree of humification, organic and mineral matter content, bulk density, chronology, volumetric growth and organic accumulation rates, carbon and nitrogen concentrations, C/N ratios, nitrogen accumulation rates, and finally magnetic analyses to detect tephra horizons. A discussion of the interrelationships between these parameters is followed by theoretical calculations of annual net primary productivity combined with multivariate analysis of the data set. Results of the analysis show that three calculated productivity peaks coincide with three periods of milder and more humid summers, at 4150–3900, 3180–3030, and 2030–1840 BP. However, the period with possibly the warmest summers, 3180–3030 BP, is interpreted also to have been characterized by cold winters. The data suggest that the periods with the coldest summers (and possibly also winters) prevailed at the earliest stage of the moss bank development, at ca. 3500 BP, and 2500 BP.

INTRODUCTION
Deep moss peat banks are a unique feature of the vegetation in maritime Antarctica (Fenton and Smith, 1982; Smith, 1984; Longton, 1985). They occur in the South Orkney and South Shetland islands and on the west coast of the Antarctic Peninsula and its offshore islands. They are predominantly ombrotrophic accumulations of the turf-forming mosses Chorisodontium aciphyllum (Hook. f. et Wils.) Broth and Polytrichum alpestre Hoppe. Usually one of them is dominant. The living surface of the banks is often partly covered by lichens, notably species of Alectoria, Bryoria, Cladonia, Sphaerophorus, Usnea, and several crustose genera. The more windswept crests of such banks are often eroded. The banks develop on a sheltered, sloping, stony, and rather well drained substratum between sea level and ca. 150 to 250 m. Only the active layer is biologically active (e.g., Wynn-Williams, 1984), since the material below is permanently frozen.

Intensive studies on moss banks on Signy Island in the South Orkney Islands and in the Argentine Islands off the midwest coast of the Antarctic Peninsula (Fenton, 1980) indicate a mean growth rate of 0.9 to 1.3 mm yr⁻¹ over the past ca. 200 yr, and an annual rate of peat accumulation of ca. 90 to 160 g m⁻² corresponding to about half the measured annual production (160–350 g m⁻² yr⁻¹). The active layer was not more than 20 to 30 cm thick,
which means that the mosses become incorporated into the permafrost and thus permanently frozen after a few centuries (Fenton, 1980). The oldest $^{14}C$ dates from the Signey Island moss banks were up to 4800 yr BP (Fenton, 1980, 1982; Fenton and Smith, 1982; Longton, 1985).

The objective of the present study was to obtain a sequence of samples through a moss bank, to describe the moss stratigraphy, to analyze bulk density, ash content, magnetic properties, microfossils, carbon and nitrogen contents, C/N ratios, and to $^{14}C$ date different strata of the sequence. These data form the basis for paleoecological and paleoclimatic interpretations.

SITE DESCRIPTION AND FIELD WORK

Two large moss banks occur on the southeast coast of Elephant Island (Figure 1). They are situated 200 to 220 m a.s.l., near Walker Point close to the upper limit where such banks occur in the Antarctic. The largest bank (Figures 2, 3) sits on the uppermost part of a local bedrock ridge, covers an area of ca. 50 x 25 m, and has a surface gradient of 10 to 30°. This exceptional bank was discovered by J. S. Allison in 1971. According to Allison and Smith (1973) and Smith (1984) its thickness is the greatest known within the Antarctic botanical zone, and it is predominantly composed of Chorisodontium aciphyllum, with some Polytrichum alpestre. The steepest gradient is upslope from the east-facing 2.5 to 3-m-high vertical wall which forms the eroded edge of the bank (Figure 2). The substratum around the moss bank consists of bare bedrock and talus. The permafrost surface on 13 December 1987 was less than 10 cm below the living moss surface, but is likely to become deeper as the summer proceeds. According to Fenton (1980) the active layer in Chorisodontium-dominated moss banks on Signy Island reached ca. 20 cm depth in the summer of 1974/75.

Using a 7.5-cm-diameter SIPRE corer, the core was
taken 6 to 7 m behind the front exposure to avoid problems of slumping. The 1.9-m core represented the entire moss sequence from the underlying talus to the surface, excluding the uppermost few centimeters of living loose moss. When the moss thawed, it shrunk to 1.5 m in spite of no observed water loss. All analyses are related to the 1.5-m thickness.

**METHODS**

**Stratigraphy**

The moss stratigraphy was documented when the core was extruded in the laboratory. The degree of humification was determined according to von Post and Granlund’s (1926) 10-degree humification scale (H1–H10), where H1 indicates that the material is not humified and H10 that it is completely humified. Apart from humification degree and color, different types of irregularities, such as folds, slides, or discordances, were also included in the stratigraphic description (Table 1).

**Physical and Chemical Analyses**

Fifty-nine levels were sampled for different types of analyses. Sample size varied between 0.5 and 4.5 cm depending on the stratigraphy. The uppermost 17 cm were sampled at each centimeter. Bulk density (g cm$^{-3}$) was...
determined for each sample. Each dried sample (105°C) was also incinerated at 550°C to measure the organic and mineral content as percentage of the dry weight. These results were used to calculate organic accumulation rates (g m⁻² yr⁻¹). Nitrogen was determined as Kjeldahl-N by a semimicro method involving digestion with H₂SO₄ (CuSO₄ as catalyst), distillation, and titration with NaOH. The carbon analyses were carried out using a LECO CR-12 autoanalyzer in which the moss material was incinerated in oxygen and the CO₂ evolved measured with an infrared detector. Two samples, 149.5–150 cm and 114.5–115 cm, were too small to allow for N and C analyses. Interpolated and extrapolated C and N values were used for those two levels to carry out the multivariate correspondence analysis (see below) on all 59 levels.

**Calculation of Annual Net Primary Productivity**

The following presumptions were made to calculate primary productivity: (1) the total nitrogen supplied has accumulated in the organic material; (2) no losses of nitrogen occur via denitrification or leaching, i.e., the nitrogen accumulated by plants is sequestered in the peat and permafrost without losses (although opposite assumptions have been discussed by, e.g., Christie [1987b]); (3) the C/N ratio is therefore determined by carbon losses through decomposition in the active layer; (4) the C/N ratio therefore reflects the depth at which decomposition is active when the peat was incorporated into the permafrost; and (5) that no further decomposition occurred after the moss was incorporated into the permafrost.

On the basis of other studies (Malmer and Holm, 1984; Malmer, 1988; Malmer et al., unpubl. data) we may also, for the present site, presume that the moss litter has a nearly constant nitrogen concentration, and thus also constant C/N ratio, independent of the amount of primary production and the annual nitrogen supply. It is possible, on the basis of the presumptions above, to calculate annual primary production and the following relationship should be valid for each level:

\[
d = p - p(h - C/N)/h \tag{1}
\]

where \( p \) is the primary production in the moss surface (g m⁻² yr⁻¹), \( d \) is the increase in amount of organic material in the permafrost (incorporation of new organic material in the permafrost) (g m⁻² yr⁻¹), \( C/N \) is the carbon/nitrogen ratio at each level, and \( h \) is a constant determined by the N concentration in the newly formed litter and expressed as its C/N ratio.

Since \( p \) also corresponds to the amount of annual input of moss litter to the active layer, provided biomass remains unchanged, \( p \) and \( d \) can be expressed as the amount of organic material being added to and removed from the active layer, respectively. A certain amount of C is also removed from the active layer through the respiration-decomposition process.

### Table 1

**Moss stratigraphy of the moss peat bank at Walker Point, Elephant Island, South Shetland Islands**

<table>
<thead>
<tr>
<th>Depth below moss surface (cm)</th>
<th>Layer no.</th>
<th>Moss peat description and humification degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-6.5</td>
<td>12</td>
<td>Blackish-brown, H2</td>
</tr>
<tr>
<td>6.5-27</td>
<td>11</td>
<td>Dark brown, H2. Folds and slidings occur at 21–25 cm. A light layer at 19–20 cm</td>
</tr>
<tr>
<td>27-33</td>
<td>10</td>
<td>Slightly dark brown, H2</td>
</tr>
<tr>
<td>33-40.5</td>
<td>9</td>
<td>Dark brown, H1</td>
</tr>
<tr>
<td>40.5-44</td>
<td>8</td>
<td>Brown, H2</td>
</tr>
<tr>
<td>44-51</td>
<td>7</td>
<td>Dark brown, H1</td>
</tr>
<tr>
<td>51-71</td>
<td>6</td>
<td>Brown, H2</td>
</tr>
<tr>
<td>71-96</td>
<td>5</td>
<td>Dark brown, H1. Cobble at 73 cm</td>
</tr>
<tr>
<td>96-114.5</td>
<td>4</td>
<td>Brownish-black, H3</td>
</tr>
<tr>
<td>114.5-115</td>
<td>3</td>
<td>Reddish-brown, H2. This layer forms an angular unconformity with the surrounding layers</td>
</tr>
<tr>
<td>115-129</td>
<td>2</td>
<td>Brownish-black, H3. A discordance at 118–119 cm</td>
</tr>
<tr>
<td>129-150</td>
<td>1</td>
<td>Black, H4</td>
</tr>
</tbody>
</table>

### Table 2

**Radiocarbon dates from the moss peat bank at Walker Point, Elephant Island, South Shetland Islands**

<table>
<thead>
<tr>
<th>Sample depth (cm)</th>
<th>Lab. no.</th>
<th>(^{14}C ) age (yr BP)</th>
<th>( \sigma^{14}C ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-5</td>
<td>Lu-3205</td>
<td>1680 ± 60</td>
<td>-23.1</td>
</tr>
<tr>
<td>17-19</td>
<td>Lu-2953</td>
<td>1890 ± 50</td>
<td>-22.2</td>
</tr>
<tr>
<td>35-37</td>
<td>Lu-2994</td>
<td>2270 ± 50</td>
<td>-22.6</td>
</tr>
<tr>
<td>76.5-78.5</td>
<td>Lu-2993</td>
<td>3050 ± 50</td>
<td>-22.1</td>
</tr>
<tr>
<td>96-98</td>
<td>Lu-2992</td>
<td>3210 ± 60</td>
<td>-23.0</td>
</tr>
<tr>
<td>121.5-124</td>
<td>Lu-2991</td>
<td>3670 ± 60</td>
<td>-22.0</td>
</tr>
<tr>
<td>124-125.5</td>
<td>Lu-2990</td>
<td>3600 ± 120</td>
<td>-22.0</td>
</tr>
<tr>
<td>147.5-149.5</td>
<td>Lu-2952</td>
<td>5350 ± 60</td>
<td>-21.5</td>
</tr>
</tbody>
</table>

The last part of the equation defines how much organic material was lost via respiration (decay) before being incorporated into the permafrost.

From equation (1) it follows that

\[
p = h \times d/(C/N). \tag{2}
\]

Since \( d \) is obtained from the peat accumulation rates, \( C/N \) can be calculated for each level, and \( h \) is defined as the highest value for the C/N ratio it is possible to calculate \( p \).

### Radiocarbon Analyses

Eight levels in the moss bank were radiocarbon dated (Table 2, Figure 4) at the Radiocarbon Dating Laboratory, Lund University. All samples were treated with HCl, and four of the samples (Lu-2952, Lu-2953, Lu-2990, and
Lu-3205) were also treated with a weak NaOH solution. The calculation of the $^{14}$C age is based on
the international radiocarbon standard (NBS oxalic acid) and the
conventional half-life for $^{14}$C of 5568 yr. The parameters
that have time as one factor, e.g., growth and accumu-
lation rates and N influx, have been calculated on cali-
brated years according to Stuiver and Pearson (1986),
Pearson and Stuiver (1986), and Pearson et al. (1986).
However, all diagrams and curves are related to $^{14}$C yr
BP on the y-axis to allow for comparisons with other
studies in the region.

**Microfossil Analyses**

Several levels were analyzed for diatom, pollen, and
spore content. However, these were unfortunately fruit-
less attempts for establishing a microfossil stratigraphy.
Only a few moss spores were found.

**Magnetic Analyses**

Magnetic analyses were undertaken on the whole
sequence. The bulk susceptibility was measured on large
samples, but the values obtained were within the margin
of error for detection. Further, moss tissue from all levels
was sampled, dried, weighed, and placed into 8-cm3 pol
styrene boxes. The magnetic remanence of each sample
was measured on a spinner magnetometer, first after
exposure of the sample to a high magnetic field of 0.7
Tesla (T) resulting in the Saturation Induced Remanent
Magnetization ("SIRM") and then after exposure to a low
reversed field of 0.1 T. The S-ratios ($S = -0.1 T/0.7 T$) and
the mass specific High Induced Remanent Magnetization
(HIRM = (1−S) × SIRM/2) were calculated.

**Multivariate Analysis**

Correspondence analysis (CA) on the data set was per-
formed using the CANOCO program (Ter Braak, 1988).
Correspondence analysis is a numerical scaling procedure
(e.g., Greenacre, 1984) that was used to detect patterns
within the entire moss bank data set. This technique or-
dinates variables and individual samples (levels) simul-
taneously on the same axes. In a multivariate data set,
as in the Walker Point moss bank, this procedure helps
to illustrate and reveal how the samples are related to the
different variables. Subtle relationships and interactions
are thus easier to explore.

Certain preconditions were established. The data input
consisted of the original numerical values of the variables
with the following units: mg g−1 organic matter for C and
N concentrations and for the amount of mineral matter,
g m−2 yr−1 for accumulation rates, mg m−2 yr−1 for N-
influx, mm yr−1 for growth rates, g cm−3 for bulk den-
sity, mAm−2 kg−1 for HIRM, and no units for the C/N
ratio. The ordination scores were scaled symmetrically
and the variables were rescaled by a square root trans-
formation (because of the large differences between the
numerical values).

**Figure 4.** An estimated age/depth curve for the moss bank based on the $^{14}$C dates in Table 2, which
are plotted with double standard errors. The curve is also based on the assumption that no significant
hiatuses exist. Based on this curve all levels analyzed for accumulation and volumetric growth rates,
N-influx, and primary productivity have been calibrated to the tree-ring time scale (Stuiver and Pearson,
1986; Pearson et al., 1986) to relate their time-dependent units to calendar years.
RESULTS

STRATIGRAPHY

Living moss on the surface of the bank was lost during coring. The moss content in 10 analyzed samples (3-130 cm) consisted of 95 to 100% Chorisodontium aciphyllum with 2 to 5% of Polytrichum alpestre at 99 cm and ca. 1% at 27 cm.

It is clear from Table 1 that the moss peat is poorly humified. The amount of organic matter is high (>95%) throughout the core, except for the lowermost section and a few other very restricted levels at ca. 4100, 3500, 3000, 1900, and 1600 BP and bulk density usually varies between 0.5 and 0.8 g cm⁻³ (Figure 5). With one exception, around 4100 BP, high bulk density values do not correspond very closely with levels rich in mineral matter, i.e., low organic values (Figure 5).

CHRONOLOGY, GROWTH RATES, AND ACCUMULATION RATES

The chronology established by the radiocarbon dates is stratigraphically consistent and according to Björck et al. (1991b) mosses give the most reliable ¹⁴C ages in Antarctica. To check the reliability of the individual dates, two adjacent sample levels (Lu-2990 and 2991, Table 2) were dated and the ages obtained agree completely. The obtained ¹⁴C ages have been used to construct a time/depth curve (Figure 4). Initial development of the moss bank began between 5400 and 5500 BP.

The volumetric growth rate has varied considerably during the development of the moss bank (Figure 6). During the first ca. 2000 yr the rate gradually increased from 0.1 to ca. 0.3 mm yr⁻¹. Then followed a marked increase and a growth rate peak (1.5–1.7 mm yr⁻¹) was reached at 3200 to 3100 BP. This peak was followed by rapidly decreasing rates and a minimum of ca. 0.3 to 0.4 mm yr⁻¹ was attained at ca. 2100 BP. Thereafter it increased slightly to 0.5 mm yr⁻¹.

The accumulation rate curve for organic matter (Figure 6) is similar to the volumetric growth rate curve. Gradually increasing values from 10 to 50 g organic matter m⁻² yr⁻¹ end with a distinct maximum at 3200–3100 BP reaching values of 80 to 110 g m⁻² yr⁻¹. Fenton (1980) estimated similar mean values for a recent Chorisod-

![Figure 5](image-url)

**Figure 5.** Amount of organic matter/dry weight and calculated values for bulk density (dry weight/volume) in the moss bank, related to the ¹⁴C chronology obtained from the ¹⁴C age/depth curve in Figure 4.

![Figure 6](image-url)

**Figure 6.** Volumetric growth rates and annual accumulation rates of organic material (both in calibrated years), related to the ¹⁴C chronology. The growth rates were calculated from the calibrated age/depth curve and thus represent the net annual increment in height after compaction and decomposition in the active layer. The accumulation rates correspond to annual deposition of organic matter per unit area, which is calculated as the ash-free bulk density multiplied with annual weight increment.

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between 40 and 400 mg m⁻² yr⁻¹, except for a second peak (40–70 g m⁻² yr⁻¹) between 2000 and 1800 BP (Figure 6). Very low accumulation rates are found at 3500 BP and at the surface (Figure 6).

PHYSICAL AND CHEMICAL STRATIGRAPHY

The carbon concentrations are fairly constant, fluctuating between 480 and 510 mg g⁻¹ organic matter (Figure 7). The few lower values are closely associated with high ash content (Figure 5). The bottommost value as well as the two peak values farther up may result from analytical errors due to an uneven distribution of mineral particles in the peat.

The nitrogen concentrations vary much more than the carbon concentrations (Figure 7). Apart from the peak of 15 mg g⁻¹ organic matter at 4100 BP the values usually vary between 3.5 and 6 mg g⁻¹. In general the N concentrations show a slightly increasing trend from 3500 to 1500 BP with three periods, 3050–2950, 2650–2450, and 2050–1850 BP, with higher values (ca. 6–8 mg g⁻¹).

The C/N ratio varies between 33 and 145 (Figure 7). Low nitrogen concentrations and hence high C/N ratios characterize the following periods: 3350–3100, 2900–2800, 2400–2200, and 1850–1750 BP. The only period with C/N ratios below 50 is at ca. 4000 BP. However, two samples from the top of the core have ratios of 55 to 60. These levels, and the 3500 and 3000 BP levels (Figure 7), are associated with high organic content (Figure 5).

Nitrogen concentrations in living moss tissues from a moss bank on Livingston Island were 4 to 6 mg g⁻¹ and with C/N ratios between 80 and 100. These values are no lower than those demonstrated for Sphagnum mosses and newly formed moss litter in unpolluted areas in the Holarctic (Malmer, 1988; Malmer et al., in press).

PRIMARY PRODUCTIVITY

On this basis of equation (2), we calculate primary productivity, since we obtain $d$ from the peat accumulation and C/N is calculated for each level. If a value of 140 is chosen for $h$ (the highest value of C/N), a curve with three distinct productivity peaks between 80 and 130 g m⁻² yr⁻¹ is obtained: 4150–3900, 3200–3000, and 2000–1850 BP (Figure 8). In between these the annual productivity reaches values of 20 to 50 g m⁻². There is an extraordinarily good correlation between the changes in nitrogen influx and primary productivity.

TEPHRA STRATIGRAPHY

At least six horizons rich in mineral matter can be detected by the physical analyses (Figure 5). The magnetic analyses (Figure 9 and Table 3) show that only two sample levels, with peaks of mineral matter (MM3 and

![Figure 7](image-url). Concentrations of carbon (C) and nitrogen (N), expressed as mg g⁻¹ organic matter, as well as the C/N ratios in the moss bank related to the ¹⁴C chronology.
to 11 zones (or time periods). The mean 1st and 2nd axis scores for each zone was then calculated and plotted in a diagram together with the scores for the variables (Figure 10).

In Figure 10, it is quite clear that most of the zones are centered around origin (Figure 10). This means that none of the variables has a dominant influence on the samples of that zone. However, a few time periods, including the surface sample, seem to be dominated by at least one or two of the variables. Three of these periods (4150–3900, 3180–3030, and 2030–1840 BP) coincide with the productivity peaks (Figure 8), but the dominance from the different variables varies (Figure 10). This suggests that different factors, such as N-concentrations, N-influx, and growth and accumulation rates, are related to the high primary productivity rates.

**DISCUSSION**

**DEPOSITION OF MINERAL MATTER**

The low ash contents (Figure 5) found in the peat strengthens the assumption that ombrotrophic conditions prevailed during peat formation. Further, the cored part of the moss bank from ca. 3500 BP and onwards was situated more than 50 cm above the surrounding mineral substratum. Therefore, deposition of the mineral matter in the four upper horizons was most likely from above (i.e., as eolian deposits). During the deposition of the two lowermost mineral horizons, the moss bank was only 20 to 30 cm. Allochthonous material washed in from the surroundings is the likely source for these mineral lenses.

**Figure 8.** Annual accumulation (in calibrated years) of N to the moss bank as well as the calculated annual (in calibrated years) net primary productivity, expressed as g m⁻² yr⁻¹, related to the ¹⁴C chronology. The calculations are described in the text.

**Figure 9.** The values for High Induced Remanent Magnetization (HIRM) in the moss tissue, expressed in mass specific units (mAm⁻² kg⁻¹), related to the ¹⁴C chronology. Note that the supposed tephra horizons are marked 1 to 5.
TABLE 3
Radiocarbon-dated peaks of mineral matter (MM1–MM6), SIRM values (SIRM1–SIRM6), HIRM values (HIRM1–HIRM5), S-ratios for each peak, and the tephra horizons according to Björck et al. (1991c)

<table>
<thead>
<tr>
<th>14C yr BP</th>
<th>5000</th>
<th>4400</th>
<th>4100</th>
<th>3850</th>
<th>3500</th>
<th>3000</th>
<th>2500</th>
<th>2250</th>
<th>2100</th>
<th>1850</th>
<th>1600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min matter peaks</td>
<td>MM1</td>
<td>SIRM1</td>
<td>MM2</td>
<td>SIRM2</td>
<td>MM3</td>
<td>SIRM3</td>
<td>MM4</td>
<td>SIRM4</td>
<td>MM5</td>
<td>SIRM5</td>
<td>MM6</td>
</tr>
<tr>
<td>SIRM peaks</td>
<td>MM1</td>
<td>SIRM1</td>
<td>MM2</td>
<td>SIRM2</td>
<td>MM3</td>
<td>SIRM3</td>
<td>MM4</td>
<td>SIRM4</td>
<td>MM5</td>
<td>SIRM5</td>
<td>MM6</td>
</tr>
<tr>
<td>HIRM peaks</td>
<td>SIRM1</td>
<td>HIRM1</td>
<td>SIRM2</td>
<td>HIRM2</td>
<td>SIRM3</td>
<td>HIRM3</td>
<td>SIRM4</td>
<td>HIRM4</td>
<td>SIRM5</td>
<td>HIRM5</td>
<td>SIRM6</td>
</tr>
<tr>
<td>S-ratios</td>
<td>0.62</td>
<td>0.85</td>
<td>0.56</td>
<td>0.82</td>
<td>0.04</td>
<td>0.99</td>
<td>0.18</td>
<td>0.13</td>
<td>0.25</td>
<td>0.06</td>
<td>0.63</td>
</tr>
<tr>
<td>Tephra horizons</td>
<td>AP13</td>
<td>AP9</td>
<td>AP8</td>
<td>AP7</td>
<td>AP6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 10. Correspondence analysis (CA) of variables (accumulation, volumetric growth, C and N concentrations, C/N ratios, nitrogen accumulation, bulk density, mineral content, and HIRM values) and 11 time periods based on the first two axes. The time periods are based on the CA ordination of the variables and the 59 sample levels. The analysis was performed by symmetric scaling of sample levels and variables and square-root transformation of the variables. The HIRM variable has such high values on the 1st and 2nd axis (40 and 196, respectively) that it cannot be included in the figure. Note that the primary productivity is not included among the variables, since one of the aims was to compare the CA with the productivity peaks (Figure 9), and since the calculated primary productivity is the result of three of the variables.
The magnetic analyses clearly suggest that HIRM1, HIRM3, and HIRM5 are of tephra layers. HIRM2 and HIRM4 have been found in other parts of the region (Björck et al., 1991c), indicating they are also tephra layers. These five tephra horizons have been named AP13, AP9, AP8, AP7, and AP6 (Table 3). The remaining MM and SIRM peaks may be explained by different sources, e.g., dust storms, since the ferrimagnetic content (mainly magnetite) is high in SIRM1 and SIRM2 (S-ratios of 0.8–0.9), while it is lower in MM1 and MM2 (S-ratios of 0.5–0.6). These intermediate values suggest that MM1 and MM2 are a mixture of tephra and the local bedrock (chloritic phylites). These older peaks can also be explained by solifluction processes, since the moss bank was shallow at the time. The two remaining peaks, MM4 and MM6, are probably of eolian origin, as the moss bank at the time of their deposition was raised significantly above the substratum. The S-ratio of these two peaks is ca. 0.6, which indicates a mixture of volcanic and local bedrock material.

**Volumetric Growth Rate**

The 0.4 m shrinkage of the core by thawing has introduced an obstacle for the calculations of volumetric growth of the frozen moss bank. The calculated growth rate of nonfrozen moss material reached a maximum of 1.0 to 1.5 mm yr$^{-1}$ between 3200 and 3000 BP (Figure 6). The rate was lower during the initial 2000 yr (0.1–0.3 mm yr$^{-1}$) than from 3000 BP to 1680 BP. The old $^{14}$C date at the moss bank surface suggests that either (1) the moss bank was eroded after 1500 BP or (2) peat accumulation stopped at 1500 BP. The surface of some maritime Antarctic moss banks is almost entirely eroded, and erosion of top layers of comparable Arctic peat deposits is well known (Engelshjøn, 1986; LaFarge-England, 1991). Probably many of these large Antarctic moss banks have reached a critical height and are unable to develop further. This might have happened on Elephant Island sometime after 1500 BP, and the moss surface would have then repeatedly been subject to erosion events.

According to Fenton (1980) the mean annual growth of *Chorisodontium* shoots was 2 mm yr$^{-1}$ on the Signy Island moss banks, while the rate in *Polytrichum*-dominated banks reached more than 3.2 mm yr$^{-1}$. However, the effective volumetric growth rate had been reduced to less than 50% of the initial shoot extension growth due to compression and decomposition. The mean rate of such moss banks has been calculated to 0.9–1.3 mm yr$^{-1}$ (Fenton, 1980). Except for the period 3200–3000 BP, the growth in height of the moss bank at Walker Point was much less. This slower volumetric growth rate is explained by less favorable moss growth conditions (climate, availability of nutrients), or, less likely at this high altitude, by a thicker active layer (greater compression and decomposition). Signy Island is located at nearly the same latitude as Elephant Island. The main climatic difference during the growing season (December–March) between these islands is the lower amount of precipitation at Signy (Allison and Smith, 1973). The mean daily summer temperature (December–March) was significantly lower on Elephant Island (−0.5°C) than on Signy (+0.5°C). The high altitude (220 m) of the Walker Point moss bank creates a less favorable local climate for moss growth than sites closer to sea level (e.g., Fenton 1980). The *Chorisodontium* bank on Signy Island is situated around 50 m a.s.l. (site E of Fenton and Smith, 1982). Fenton and Smith (1982) list eight factors which determine the extent of individual moss banks. The main factor distinguishing Fenton's (1980) sites from the moss bank at Walker Point is “Harshness of the environment; wind is the critical factor here and obviously related to altitude” (Fenton and Smith, 1982: 234). The 200- to 300-yr long period with high growth rates (Figure 6) could be explained by an ameliorated summer climate with higher temperatures and less wind. Additionally, if colder winters decreased the thickness of the active layer, the accumulation rate would increase. This last factor alone cannot explain the dramatic changes in growth rate (Fenton, 1980).

**Accumulation Rates and Concentrations of Nitrogen and Carbon**

Similar to all other peat deposits, the accumulation rate at Walker Point was determined by the balance between the primary production of the living and actively growing mosses at the surface and the decomposition losses in the active layer before the remaining organic matter becomes incorporated in the permafrost (Clymo, 1978, 1984). In temperate or boreal peatlands decomposition of organic matter continues by anaerobic decay after organic matter has been transferred below the water table, although at a much slower rate. On these bogs the position of the water table defines aerobic versus anaerobic activity. In peatlands with permafrost, it is the seasonal depth of thaw which represents the active layer. Thus in a frozen peat deposit, the organic matter will closely reflect the chemical and physical conditions in the peat prior to incorporation into the permafrost. Except for the peak values at ca. 3100 BP, these accumulation rates are low when compared to ombrotrophic bog peat in temperate or boreal areas of northern latitudes (Clymo, 1983, 1984).

The variation in the nitrogen accumulation rate (Figure 8) follows that of the accumulation of organic matter (Figure 6). The values either vary between 0.1 and 0.2 g m$^{-2}$ yr$^{-1}$ or reach peaks between 0.3 and 0.4 g m$^{-2}$ yr$^{-1}$, with the exception of the few lowermost samples. At present a wet deposition of nitrogen on bogs in the range 0.2 to 0.6 g m$^{-2}$ yr$^{-1}$ is characteristic for nonpolluted areas with ombrotrophic bogs in the temperate and boreal regions of the Holarctic (Munger and Eisenreich, 1983; Malmer, 1988; Malmer et al., in press).

In experiments of nitrogen application to the surface of *Sphagnum*-dominated bogs, all of the nitrogen supplied is taken up by growing mosses (Pakarinen, 1978; Damman, 1978; Malmer and Nihlgård, 1980; Lee et al., 1986; Malmer, 1988). Smith (1972, 1979) reported that 68 samples of four moss association groups, including *Poly-
*trichum–Chorisodontium* peat, from Signy Island had a mean pH of 4.3 to 4.4. The moss at Walker Point, growing in an acid environment, is thus not very different from these sites or a similar arctic or subalpine peat deposit dominated by *Sphagnum* species. Several studies in temperate, boreal, and subalpine areas have also demonstrated that nitrogen losses through leaching or denitrification from ombrotrophic bogs are small (Verry, 1975; Martin and Holding, 1978; Rosswall and Granhall, 1980; Verry and Timmons, 1982; Urban and Eisenreich, 1987; Clymo et al., in press). All nitrogen accumulated by the plants is either recycled within the plants or contained in the organic matter forming the litter, and finally, deposited in the peat below the active layer. The relocation of N within the plants results in lower concentrations in the plant litter than in the living and actively growing parts (Malmer and Nihlgärd, 1980; Malmer, 1988; Rydin and Clymo, 1989).

The variation in nitrogen accumulation rate (Figure 8) suggests that the nitrogen supply has varied for different periods since assimilation of available nitrogen by mosses is complete. Nitrogen is generally thought to limit plant productivity in harsh environments, such as at Walker Point (Rosswall and Granhall, 1980). Thus, during periods with high nitrogen supply, the moss productivity including carbon accumulation, should increase. Slight variations in nitrogen concentrations within living moss tissue or moss litter may occur, but these are small compared to the variation in moss productivity (Malmer, 1988, 1990; Malmer et al., in press).

If the nitrogen concentrations in the mosses and moss litter remained constant through time, the N concentration and C/N ratio (Figure 7) in the peat will mainly depend on the loss of carbon compounds during decomposition in the active layer. From comparison with a sample of living moss from a similar bank on Livingston Island, which contained 4 to 6 mg g⁻¹ of nitrogen and from other studies on peat mosses (e.g., Christie, 1987a) it can be assumed that N concentrations in moss litter below 3.3 mg g⁻¹ and C/N ratios above 140 are very rare (Malmer and Holm, 1984; Malmer, 1988, 1990; Malmer et al., in press; Malmer and Wallén, unpubl. data). The N concentrations and the highest C/N ratios observed at Walker Point (Figure 7) approximate these values. The variation of the C/N ratio therefore reflects the intensity of decomposition in the active layer. Periods with high C/N ratios suggest low decay losses in the active layer before the organic matter was incorporated into the permafrost, perhaps not more than 10 to 20%. The period of the lowest quotient indicates losses of up to 60 to 70% around 4000 BP. With a C/N ratio of up to 110 in the moss litter, the C/N ratio in the frozen peat, as well as in the peat just above the permafrost, was only 25 to 30 for a subarctic bog in northern Sweden (Rosswall and Granhall, 1980; Malmer and Nihlgärd, 1980). This implies that more than 75% of the carbon originally accumulated in the plant litter has been lost through decomposition (Malmer and Holm, 1984), which greatly exceeds the potential decomposition at Walker Point.

The length and temperature of the growing season must be the most critical factors that determine the decay rate in the active layer at this site. The variations in the C/N quotient suggest that periods of low decomposition prevailed at 3300–3100, 2800, and 1800 BP (Figure 7), while high decomposition rates prevailed between 4100–3900 BP.

Good correlation between high ash content (Figure 5) and high nitrogen concentrations (Figure 7) shows that other factors are important. In the lower parts of the sequence cryoturbation may have occurred which exposed mosses to decay for longer periods than at higher levels. Greater decay rates associated with the higher ash concentrations higher up in the sequence could have been caused by a darker color of the moss surface just after deposition of the mineral (tephra) matter. This enhanced the heat absorbance of the moss, raised the surface temperature, and increased the supply of mineral nutrients. Microbial activity is not only limited by climatic conditions and nitrogen but also by mineral nutrients. If the tephra fallout on the moss bank (Figure 9) is compared with some of the nitrogen peaks (Figure 7) there is a close correlation between these factors if a small time-lag between the tephra deposition and the increased nitrogen values is taken into account.

For ombrotrophic bogs in temperate and boreal areas it has been shown by mathematical modeling (Clymo, 1984) that it is the residence time for the organic matter in the acrotelm that determines the rate of peat accumulation. Variation in the productivity is less important, since the carbon losses from the acrotelm amounts to 80 to 90% of the net annual carbon accumulation in the plant cover (Malmer and Holm, 1984). If the carbon losses in the active layer are only 50% or less, a variation in productivity would affect the peat accumulation rate much more.

Like the volumetric growth rate, the accumulation rate at Walker Point (Figure 6) is much less than that reported from Signy Island (Fenton, 1980). Here the annual productivity was estimated to be 160 to 300 g m⁻² of which ca. 50% was lost through decay before being incorporated into the permafrost. The low nitrogen concentrations and high C/N quotients suggest that the much slower accumulation at Walker Point cannot be the result of a higher decay rate, but must be explained by a smaller productivity than that on Signy Island. A mean annual net productivity of 20 to 50 g m⁻² may be a more realistic value for the Walker Point site (cf. Figure 8) with its rather harsh local climate. Similar rates have been reported from peat-forming habitats in arctic and subarctic areas (e.g., Rastorfer, 1978; Oechel and Sveinbjörnsson, 1978; Rosswall and Granhall, 1980).

Prior to 3000 BP both the accumulation and volumetric growth rates (Figure 6) reached values similar to and even higher than the recent mean value for a *Chorisodontium* moss bank on Signy Island (Fenton, 1980). Otherwise, the Walker Point values were lower, except for a short accumulation rate peak at ca. 1900 BP. The two periods with increased accumulation rates are characterized by
high C/N quotients which suggests a low decay rate. The high supply of nitrogen (Figure 8) and the much greater variation in the C/N quotient than in the accumulation rate suggest great variation in the moss productivity during the whole sequence.

No doubt the variation in accumulation and growth rates is climatically induced. A significant increase in moss production strongly suggests longer and/or milder summers as would a low C/N quotient. A high C/N quotient similarly suggests short and cold summers with a thin active layer. However, the problem is complicated because a rapid moss growth and carbon accumulation rate shortens the residence time for the organic material in the active layer and thus decreases the decay and increases the C/N quotient. This process may have been active at 2000 BP when the peak in the accumulation rate started with a distinct minima in the C/N quotient.

Primary Productivity and Correspondence Analysis

A number of complex feedback mechanisms influence the parameters analyzed in this study. These complex patterns may be simplified by two types of mathematical calculations: (1) estimates of the net primary productivity in the moss bank through time, and (2) multivariate analysis (correspondence analysis) to reveal the underlying structure of the interrelated data.

According to the presumptions given above and equation (2) the moss bank was characterized by high productivity during three rather short time periods (Figure 8). Two questions arise from these results: (1) can the validity of the curve in Figure 8 be tested? and (2) what conditions produced these productivity peaks?

The correspondence analysis (Figure 10) undoubtedly supports the existence of the three productivity peaks. It also suggests which variables are related to these peaks. Therefore, on the basis of the discussion about the variables and the mathematical and statistical analyses we think certain conclusions can be drawn about the climatic/environmental changes that the moss bank has experienced. In this context it should be pointed out that changing primary productivity rates may, at least partly, be an effect of large bird colonies moving in and out of the area (Allison and Smith, 1973) since such reasons may partly explain varying N-influx values (Christie, 1987b). On the other hand, changes in bird activity may also have been a direct response to climatic/environmental changes.

A Paleoclimatic Reconstruction during the Moss Bank Development at Walker Point

Moss banks are a potential archive of palaeoenvironmental records in Antarctica for reconstructions of the Holocene. They give reliable 14C ages and many physical parameters can be analyzed. Although the interrelationships between different parameters are often complex, they can provide valuable information on paleoclimate.

In contrast to ombrotrophic bogs of northern temperate and boreal regions, the accumulation rate of Antarctic moss banks varies in response to changes in moss productivity rather than in decomposition of the organic matter. Except for short periods, carbon loss from moss litter does not exceed 40% before incorporation into the permafrost.

The basal date of the moss bank suggests that the area became deglaciated some time before 5500 BP, indicating that Elephant Island was more extensively covered by glaciers before the moss bank began to develop. On the basis of the same type of evidence, Smith (1990) suggests a similar development for Signy Island.

On the basis of the discussion above and the CA ordination (Figure 10), the following developmental stages of the moss bank may be recognized:

- **5500–4320 BP**: Rather high mineral input—low decomposition, thin active layer, which suggests cold (short) summers and/or cold (long) winters, solifluction, and eolian processes in a newly (locally) deglaciated environment.
- **4320–4150 BP**: A transition period with gradually warmer climate but still with a rather high mineral input.
- **4150–3900 BP**: Low C/N ratio, high N concentrations and influx, rather low accumulation of organic matter and volumetric growth rates, high moss productivity—infers high decomposition and a thick active layer, warm (long) summers, mild (short) winters. The high values for N-accumulation may indicate inputs from birds and/or increased precipitation from northern, milder, and more N-rich air masses.
- **3900–3180 BP**: Increasing C/N ratios, gradually increasing accumulation and growth rates—suggests decreasing decomposition, thinner active layer, colder winters and possibly also colder summers. The increased accumulation and growth rates may be a direct effect of a decrease in decay.
- **3180–3030 BP**: High C/N ratios and high N-influxes, very high accumulation and growth rates, very high productivity—indicates low decomposition, thin active layer, very favorable moss growth conditions with warm (humid) summers characterized by a large increase in precipitation from more N-rich air masses from the north, cold winters. Local bird colonies (especially penguins) could also have been at least partly responsible for the high N-influx values by producing nitrogenous aerosols.
- **3030–2030 BP**: No dominating variable—“mean” climatic conditions.
- **2030–1840 BP**: Low C/N ratios, rather high N-influxes and N concentrations, increasing accumulation rates, high productivity—high decomposition, rather thick active layer, good moss growth conditions with warm (humid) summers and probably mild winters as an effect of increased influence from northern air masses. Possibly increased influence from bird colonies.
- **1840–1580 BP**: No dominating variable—“mean” climatic conditions. The surface sample, 1580 BP, is different from the others since it has probably been exposed to a variety of conditions since it was growing on the moss bank surface. As such it does not give any paleoclimatic information.
CONCLUSIONS

The accumulation of peat at Walker Point is determined by a delicate balance between the thermal regime, regulating the seasonal depth of thaw, and various factors controlling primary productivity. The optimum conditions for peat accumulation at this site are warm humid summers with high nitrogen influx that stimulate primary productivity and long cold winters that enhance the aggradation of permafrost.

In the past these conditions could have been produced by increased influence of humid (N-rich) and warmer air masses from the north during summer, while winters would have been more continental by an increased influence from the cold and arid air masses in the south. Such conditions might have prevailed on Elephant Island between ca. 3200 and 3000 BP, while the periods 4150–3900 and 2030–1840 BP seem to have had both mild summers and winters. Studies on sediments in Midge Lake on Livingston Island (Figure 1) show that the mildest and most humid summer conditions prevailed between 3200 and 2700 BP with another mild pulse at 2000 BP (Björck et al., 1991a).

The periods with least favorable conditions for primary productivity, moss growth, and accumulation of organic matter, indicating both colder summers and winters, occurred toward the beginning of the moss bank development, 5500–4300 BP, at ca. 3500 BP and at 2500–2400 BP.

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