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Late Holocene climatic changes in Tierra del Fuego based on multiproxy analyses of peat deposits

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Abstract

A ca. 1400-yr record from a raised bog in Isla Grande, Tierra del Fuego, Argentina, registers climate fluctuations, including a Medieval Warm Period, although evidence for the 'Little Ice Age' is less clear. Changes in temperature and/or precipitation were inferred from plant macrofossils, pollen, fungal spores, testate amebae, and peat humification. The chronology was established using a ^{14}C wiggle-matching technique that provides improved age control for at least part of the record compared to other sites. These new data are presented and compared with other lines of evidence from the Southern and Northern Hemispheres. A period of low local water tables occurred in the bog between A.D. 960–1020, which may correspond to the Medieval Warm Period date range of A.D. 950–1045 generated from Northern Hemisphere tree-ring data. A period of cooler and/or wetter conditions was detected between ca. A.D. 1030 and 1100 and a later period of cooler/wetter conditions estimated at ca. cal A.D. 1800–1930, which may correspond to a cooling episode inferred from Law Dome, Antarctica.
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Introduction

Numerous paleoecological studies have described the late Quaternary climate and vegetation history of Tierra del Fuego and southern Patagonia (Ashworth et al., 1991; Borromei, 1995; Heusser, 1989, 1995, 1998; Markgraf, 1983, 1993; McCulloch and Davies, 2001; Pendall et al., 2001; Quattrocchio and Borromei, 1998; White et al., 1994), but to date the region lacks detailed plant macrofossil, testate amebae, and peat humification analyses (Barber et al., 1994; Charman et al., 1999; Mauquoy et al., 2002). Furthermore, no ^{14}C wiggle-match chronologies (Blaauw et al., 2003; Kilian et al., 1995) are currently available to establish the precise timing of local vegetation and potential climate-induced changes spanning the last ca. 1300 yr. This dating technique simply relies on the nonlinear relationship be-

tween ^{14}C age and calendar age to match the shape of a sequence of closely spaced ^{14}C dates with the ^{14}C calibration curve in order to improve precision. This paper addresses the chronological shortcoming identified in the review of Rabassa et al. (2000), in combination with new multiproxy analyses of peat deposits exposed in peat works in the Valle de Andorra, located ca. 10 km to the northeast of Ushuaia, Tierra del Fuego, Argentina (S 54° 45′, W 68° 18′, ca. 180 m asl, see Fig. 1).

Materials and methods

Peat monoliths of 1 m depth were collected from sections exposed in the peat works using metal boxes (50 × 15 × 10 cm). Intact raised peat bogs ca. 1.5 km to the westnorthwest of the peat works were used for the collection of plant macrofossil type material and analyses of testate amebae from varying positions above local water tables (local water table depths spanned 0–101 cm, pH range 4.72–6.05). The

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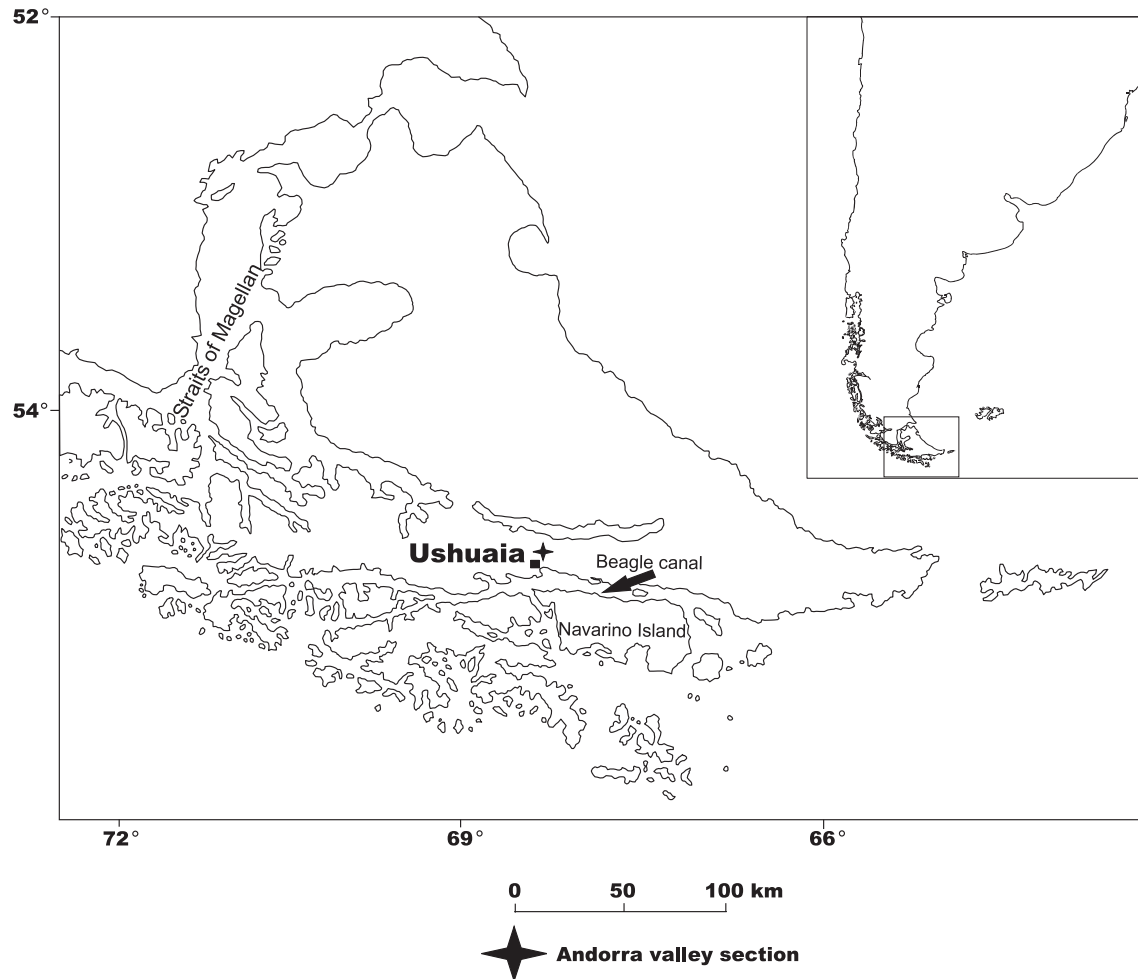E-mail address: mauquoy@science.uva.nl (D. Mauquoy).

Fig. 1. Map of Tierra del Fuego, showing study site location at Ushuaia. Box in index map shows area of enlargement.

local vegetation cover is primarily composed of *Marsippospermum grandiflorum*, *Carex curta,* and *Sphagnum magellanicum*, which grows from the highest hummock microforms (depth to local water tables of >60 cm) down to pool margins. Pool microforms are infrequent, but possess *Sphagnum* sect. *Cuspidata* and *Tetroncium magellanicum* which grows at the pool margins. *Empetrum rubrum* and *Nothofagus antarctica* appear to be restricted to microforms where local water tables are lower. Forests of *Nothofagus pumilio* surround the bogs in the Valle de Andorra. The mean annual temperature and precipitation is estimated at 6°C and 450–600 mm, respectively, and annual cloudiness surpasses 60% (values taken from Roig et al., 1996).

Macrofossil samples were collected at contiguous 1-cm sample intervals from the 1-m-long Valle de Andorra (AND1) peat core. These were boiled with 5% KOH and sieved (mesh diameter 100 μm). Macrofossils were identified using a binocular microscope (x10–50). Abundances of each peat component were expressed as percentage volume of the subsample (ca. 5 cm^3). Microfossil samples of ca. 1 cm^3 volume (precise volume estimated by immersion) were treated with KOH and acetolyzed (Fægri and Iversen, 1989).

To estimate microfossil concentrations *Lycopodium* spores were added to the sample (Stockmarr, 1971). Pollen and fungal microfossils were counted at 2-cm sample intervals (pollen sum of 200 to 500 grains per sample). Fungal microfossils are presented as percentages of 100 pollen grains (aquatics and cryptogams excluded).

Pollen identifications were made using modern reference material in the Universidad Nacional del Sur Palynology Laboratory and published descriptions and keys (Heusser, 1971; Markgraf and D'Antoni, 1978). The degree of peat humification of 100 contiguous samples was assessed using a modified version of the Bahnson colorimetric method (Blackford and Chambers, 1993). Testate amebae from a further 100 contiguous samples were analyzed following Hendon and Charman (1997). Counting was done until 150 testate amebae were recorded.

Thirteen samples of *Sphagnum* leaves and/or stems were radiocarbon dated using AMS (Kilian et al., 1995, 2000; Table 1). Only *Sphagnum* subfossils (leaves and stems) were selected from the macrofossil samples. Samples were cleaned to remove roots of Ericaceae and Cyperaceae and fungal mycelium, transferred to a petri dish containing

Table 1
Radiocarbon and calibration/wiggle-match date results for AND1

Date (No.)	Ua number	$\delta^{13}C$ (‰)	^{14}C age (^{14}C yr B.P.)	^{14}C age (^{14}C yr B.P.) with 30-year Southern Hemisphere offset (Mook, 1986)	Laboratory standard deviation (B.P.)	Midpoint sample depth (cm)	CALIB 4.3 calibration (2 σ range and midpoint rounded to the nearest decade)	Wiggle-match date— best match using maximum likelihood rounded to the nearest decade	Weighted least squares confidence intervals for wiggle-match date (min, max, 2 SD range)
1	19905	−27.7	200	170	45	31.5	cal A.D. 1655–1950; cal A.D. 1800	X	X
2	18763	−29.5	355	325	60	49.5	cal A.D. 1444–1662; cal A.D. 1550	X	X
3	19906	−25.4	1005	975	45	67.5	X	cal A.D. 1100	cal A.D. 1090–1156
4	19907	−26.6	865	835	45	69.5	X	cal A.D. 1080	cal A.D. 1073–1123
5	19908	−26.2	840	810	45	71.5	X	cal A.D. 1060	cal A.D. 1055–1090
6	19909	−25.5	995	965	40	73.5	X	cal A.D. 1040	cal A.D. 1038–1057
7	19910	−25.4	1010	980	40	75.5	X	cal A.D. 1020	cal A.D. 1018–1028
8	19911	−25.6	1040	1010	40	77.5	X	cal A.D. 1010	cal A.D. 984–1008
9	19912	−26.3	1115	1085	40	79.5	X	cal A.D. 990	cal A.D. 951–990
10	19913	−25.9	1135	1105	40	81.5	X	cal A.D. 970	cal A.D. 918–972
11	19914	−24.7	1205	1175	40	83.5	X	cal A.D. 950	cal A.D. 884–955
12	19915	−25.8	1250	1220	40	85.5	X	cal A.D. 930	cal A.D. 851–937
13	18764	−27.5	1415	1385	65	99.5	cal A.D. 540–776 cal A.D. 660	X	X

deionized water and then pretreated for radiocarbon analysis (Speranza et al., 2000). A ^{14}C offset was applied to these Southern Hemisphere samples although the exact value is the

Table 2
Macrofossil and fungal microfossil zonation for AND1

Zone AND1-a (100–85 cm). Peat matrices are largely composed of *Sphagnum magellanicum* (72–93%), with relatively low amounts of *Empetrum*/Ericaceae roots (2–15%). Type 126 Hyphopodia of *Gaeumannomyces* sp. confirm the presence of *Carex* sp. (Pals et al., 1980).

Zone AND1-b (84–81 cm). A decrease in *S. magellanicum* (67–58%) was recorded in addition to an increase in *Empetrum*/Ericaceae roots (25–30% of the peat matrices), indicating a reduction of local water table depths. Abundances of Type 811 spores increase.

Zone AND1-c (80–48 cm). Percentages of *S. magellanicum* and detached *Sphagnum* stems increase (maximum values of 93 and 15% were recorded, respectively). Between 80 and 68 cm fungal Types 810 and 811 are almost absent. Elevated values of Type 810 ascospores occur between 57 and 53 cm. Increased charcoal occurs from 53 to 49 cm, indicating the occurrence of local fires.

Zone AND1-d (47–27 cm). Fluctuations in local water table depths may have occurred, since there are clear oscillations in the percentages of identifiable *Sphagnum* and *Empetrum*/Ericaceae roots. Sequential increases in Types 812, 811, and 810 fungal microfossils occur.

Zone AND1-e (26–14 cm). Increases in *S. magellanicum* and a reduction in *Empetrum*/Ericaceae roots suggest that an increase in mire surface wetness occurred. Type 810 ascospores decline.

Zone AND1-f (13–9 cm). The lowest values of *S. magellanicum* and high values of *Empetrum*/Ericaceae roots and unidentifiable organic material (40 and 25%) indicate a marked decrease in mire surface wetness. The highest values of Type 5 conidia were recorded here, supporting the occurrence of dry conditions (van Geel, 1978).

Zone AND1-g (8–0 cm). Mire surface wetness appears to have increased as high values of *S. magellanicum* recur. Fungal microfossils are very infrequent.

Zonation—optimal splitting by information content, PSIMPOLL 4.10.
Features of zones.

subject of continuing research (see Stuiver et al., 1998, for details). We subtracted 30 years from all radiocarbon measurements following the recommendations of Mook (1986).

The ^{14}C ages of the samples from 68 to 86 cm (dates 3–12, Fig. 2) have been converted to calendar ages using ^{14}C wiggle-match dating (van Geel and Mook, 1989), assuming a constant peat accumulation rate. The best fit (using maximum likelihood) and confidence intervals (using weighted least squares) were calculated for each date after the technique of Blaauw et al. (2003; Fig. 2). The basal date at 100 cm and upper samples at 50 and 32 cm were calibrated using CALIB 4.3, since an insufficient density of ^{14}C dates was available to wiggle-match these sections of the peat stratigraphy. Zonation of the record of local vegetation in the macrofossil diagram (Fig. 3 and Table 2) was performed using optimal splitting by information content (Bennett, 1996; Birks and Gordon, 1985) within Psimpoll version 4.10. Seeds of *E. rubrum* and the macroscopic charcoal fragments were excluded from this zonation procedure, because they were not counted as percentages. The fungal microfossils were also excluded from the zonation because their counts are an order of magnitude larger than the plant macrofossils and would therefore heavily bias the zonation of the local vegetation development. Relationships between the plant macrofossil components and the fungal microfossils were explored using principal components analysis (PCA) (Fig. 4).

Results

The AND1 macrofossil stratigraphy registers low local water tables in zones AND1-b, AND1-d, and AND1-f (Fig. 3), because percentage abundances of *Empetrum*/Ericaceae
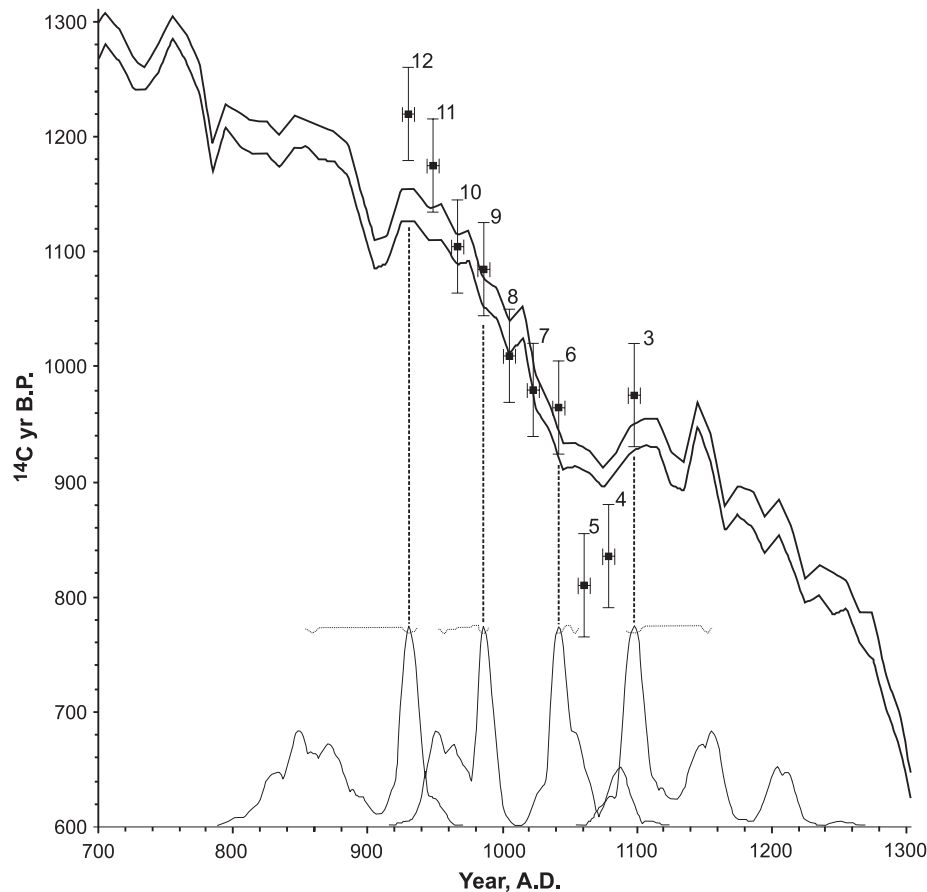
Fig. 2. Numerical wiggle-match fit of ^{14}C AMS dates 3–12. Thick lines show 1 standard deviation (σ) error envelope of INTCAL98 calibration curve (Stuiver et al., 1998). Vertical bars of ^{14}C samples show 1-σ error bars; horizontal bars show deposition period of the samples. Projected on the calendar year axis are the WLS (weighted least squares, concave shapes) and MLH (maximum likelihood, convex shapes) probability distributions of selected dated levels. The vertical scale is arbitrary. Maximum values of WLS indicate 2-σ limits. The dated levels are placed on the calendar axis as proposed by the optimal MLH solution (after Blaauw et al., 2003).

roots are relatively high. The PCA ordination (Fig. 4) shows that the fungal microfossils (Types 5, 126, 810, 811, 813, and 814; see Fig. 5) occur with the plant macrofossils, indicative of dry conditions (*Empetrum*/Ericaceae roots and wood and unidentifiable organic material), since the angles between these vectors are relatively low. A clear separation between these components and *S. magellanicum* suggests the primary direction of variance of PCA axis 1 represents a wetness gradient of the mire surface (increasing numbers on the *x* axis indicate decreasing mire surface wetness). Furthermore, high PCA axis 1 values of the samples are associated with low transmission values (indicating high peat decomposition), high pollen concentrations of *Empetrum*/Ericaceae (*Empetrum* is a species which indicates low mire surface wetness; Heusser, 1989), and relatively high percentages of *Assulina muscorum* and *Corythion dubium* (Fig. 6, zonation details Table 3). The 15 surface samples confirm the relationship between relatively low, local, water tables and increased abundance of *A. muscorum* (Fig. 7). Three periods of high surface wetness occurred between ca.

A.D. 890–950 (AND1-II), A.D. 1030–1100 (AND1-IV), and A.D. 1800–1930 (AND1-VI). Zones AND1-I, AND1-III, and AND1-VII (ca. A.D. 660–870, 960–1020, and 1940–1950, respectively) seemingly represent warmer and/or drier conditions.

Discussion

The paleoclimatic interpretations offered here should be applied cautiously, as only a single borehole was examined. Multiple cores from raised peat bogs have shown that it is not always possible to replicate changes in mire surface wetness (Mauquoy et al., 2002), and the possibility exists that the data register only local successional changes. The latter appears unlikely because changes in the peat stratigraphy could be followed over tens of meters in the 1-m-deep drainage ditches from which the samples were obtained. With the exception of the section dated by ^{14}C wiggle-matching, the dating control is relatively poor, and so the
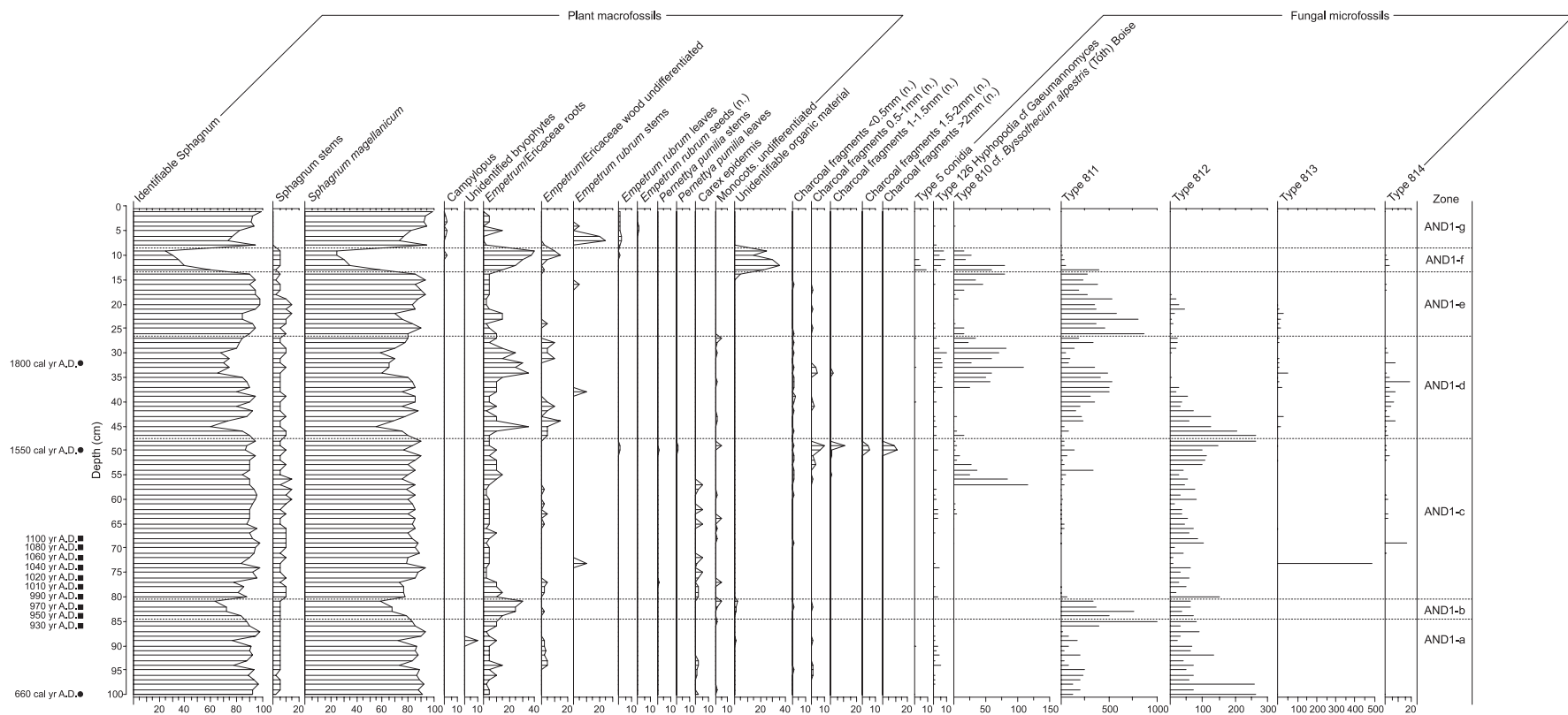
Fig. 3. AND1 macrofossils and macroscopic charcoal particles. Volume abundances of all components are expressed as percentages with the exception of *E. rubrum* seeds and charcoal fragments, which are presented as the number (n) found in each ca. 5-cm³ subsample. Fungal microfossils are presented as percentages related to 100 pollen grains (aquatics and cryptogams excluded).

Table 3
AND1 composite diagram zonation

Zonation—"eye" only	Reconstructed mire surface
Features of zones	Wetness with date ranges
Zone AND1-I (99–89 cm). In this zone the highest concentration values of *Empetrum*/Ericaceae were recorded. Peat transmission is relatively low.	Low mire surface wetness ca. A.D. 660–870[a]
Zone AND1-II (88–84 cm). *Empetrum*/Ericaceae pollen concentrations decrease and lower PCA axis 1 values were recorded.	High mire surface wetness ca. A.D. 890–950
Zone AND1-III (83–76 cm). A new resurgence of *Empetrum*/Ericaceae is recorded, followed by increases in *Assulina muscorum*.	Low mire surface wetness ca. A.D. 960–1020
Zone AND1-IV (75–68 cm). Peat transmission increases, *A. muscorum* abundances decrease, and low values of PCA axis 1 scores are recorded.	High mire surface wetness ca. A.D. 1030–1100
Zone AND1-V (67–33 cm). Fluctuations in transmission, *Empetrum*/Ericaceae pollen concentrations and PCA axis 1 scores occur.	Oscillations in mire surface wetness ca. A.D. 1130–1790[a]
Zone AND1-VI (32–12 cm). Low concentrations of *Empetrum*/Ericaceae occur and PCA axis 1 scores decrease.	High mire surface wetness ca. A.D. 1800–1930[a]
Zone AND1-VII (11–8 cm). Low peat transmission, high values of *A. muscorum* and *Corython dubium*, high values of *Empetrum*/Ericaceae and high PCA axis 1 scores all occur.	Low mire surface wetness ca. A.D. 1940–1950[a]
Zone AND1-VIII (7–0 cm). Increases in peat transmission, decreases in concentration values of *Empetrum*/Ericaceae and PCA axis 1 scores occur.	High mire surface wetness ca. A.D. 1960–present[a]

[a] Ages linearly interpolated between the ^{14}C AMS dates that were calibrated (midpoint of the 2-σ calibration range).

age ranges for zones AND1-I, AND1-II, and AND1-V to AND1-VIII inclusive (Fig. 6) can provide only an approximate age for the reconstructed changes in mire surface wetness. We therefore focus attention on the inferred paleoclimatic changes registered in zones AND1-III and AND1-IV, for which have greater confidence in the chronology.

Evidence for the Medieval Warm Period

The evidence for drier conditions in zone AND1-III (ca. cal A.D. 960–1020) indicating warming seems to correspond to the Medieval Warm Period (MWP, as defined in the Northern Hemisphere). This interval compares well to the date range of A.D. 950–1045 based on Northern Hemisphere extratropical tree-ring data (Esper et al., 2002). These dendrochronological data also suggest the MWP may have begun in the early A.D. 900s. The extent, timing, and nature of the Medieval Warm period are uncertain. According to Broecker (2001), evidence for a global Medieval Warm Period is circumstantial and

because of the relative scarcity of Southern Hemisphere paleoclimatic data, Crowley and Lowery (2000) suggest the term Medieval Warm Period should be restricted to the Northern Hemisphere only. Our reconstruction for warm/dry conditions between ca. A.D. 960–1020 closely agrees with Northern Hemisphere tree-ring evidence for the MWP and shows that the MWP was possibly synchronous in both hemispheres, as suggested by Villalba (1994).

Evidence for Little Ice Age climatic deteriorations

Zone AND1-IV suggests cooler and/or wetter conditions between ca. A.D. 1030–1100, which may represent a Southern Hemisphere precursor to the Little Ice Age (LIA). Regional evidence for climatic deteriorations is suggested by advances of a lobe of the Bahia Pia glacier system in the Cordillera Darwin, Tierra del Fuego (Kuylenstierna et al., 1996), reaching one of its maximum positions between 940 and 675 B.P. (cal A.D. 980–1260 and cal A.D. 1220–1420 at 2 σ, respectively). Our high-precision ^{14}C chronology possibly refines this agerange for the start of cooling in Tierra del Fuego. A temperature profile from Law Dome core (Dahl-Jensen et al., 1999) has minima at A.D. 1250 and 1790–1850, and the magnetic susceptibility record of the Antarctic Palmer Deep marine core (Domack et al., 2001) also indicates a possible LIA signal at ca. 700 B.P. (cal A.D. 1250). Our age range for the first cooling episode predates this (ca. cal A.D. 1030–1100), even with the maximum weighted least squares estimate for date 3 (A.D. 1156, Table 1). We do not have sufficiently good dating control in zone AND1-VI, but there is a possibility that the evidence for cooler and/or wetter conditions at ca. A.D. 1800–1930 (low concentrations of *Empetrum*/Ericaceae and low PCA axis 1 scores) may correspond to a period of low temperatures (A.D. 1790–1850) identified by Dahl-Jensen et al. (1999) and to tree-ring evidence for cool summer temperatures in Tierra del Fuego at ca. A.D. 1850 and A.D. 1880 (Boninsegna et al., 1989).

The AND1 peat stratigraphy displays increased mire surface wetness between ca. A.D. 1030–1100 and ca. cal A.D. 1800–1930. However, the chronology for this period of cooler and/or wetter conditions is poor. Dating control for the peat stratigraphy postdating zone AND1-IV is also poor, but fluctuations in mire surface wetness registered in zone AND1-V may correspond to another cooler/wetter period identified in the wider study region. For example, summer temperature reconstructions from tree-rings in northern Patagonia (ca. 1500 km to the north northwest of the Valle de Andorra) suggest a warm period occurred from A.D. 1080–1250, followed by a prolonged cold period from A.D. 1270 to A.D. 1660, possibly peaking around A.D. 1340 and 1640 (Villalba, 1990, 1994). This period does not appear to have been uniformly cold, since the tree-ring data suggest warming occurred between A.D.
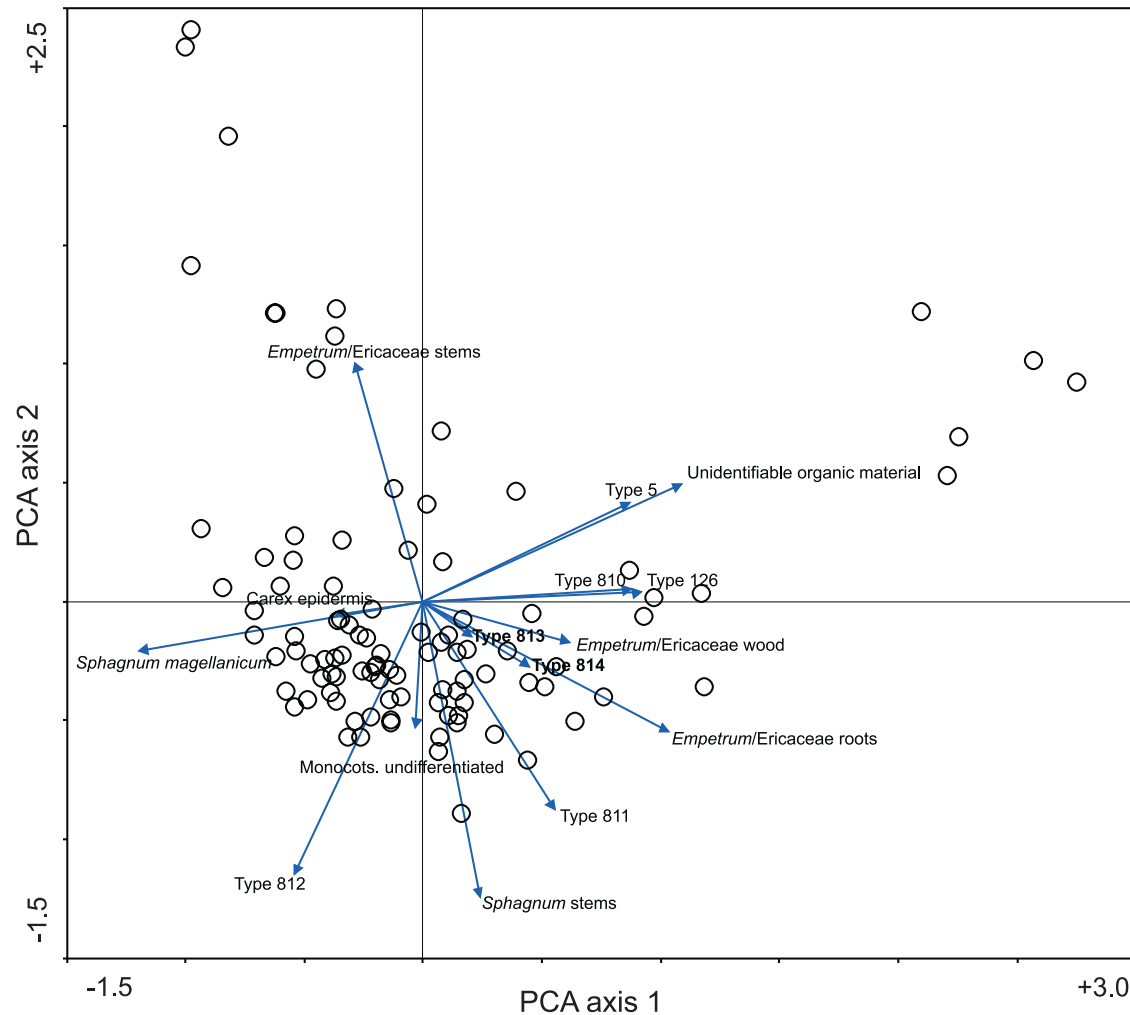
Fig. 4. Principal components analysis biplot of the AND1 plant macrofossil and fungal microfossil data. The ordination was performed using CANOCO for Windows version 4.02, using the following options: focus scaling on interspecies correlations, species scores divided by standard deviation, species data log transformed, species centered and standardized. *Campylopus*, *E. rubrum* leaves, *Pernettya pumilia* stems and leaves were excluded.

1380 and 1520. Finally, warmer conditions were reconstructed between A.D. 1720 and 1790 (Villalba, 1990). An advance of the Soler Glacier in the North Patagonian Icefield has been dated using in situ tree remains to ca. A.D. 1222–1342 (Glasser et al., 2002), which supports the climatic reconstructions of Villalba. More records with greater numbers of ^{14}C dates could serve to resolve the chronology of the evidence for climate change in Tierra del Fuego and establish if the LIA climatic deteriorations detected in the wider study region and the Northern Hemisphere (Luckman and Villalba, 2001) also occurred here.

Appendix A. Descriptions of newly distinguished types in core AND1

A.1. Type 810 (Figs. 5: 2, 3a, 3b)

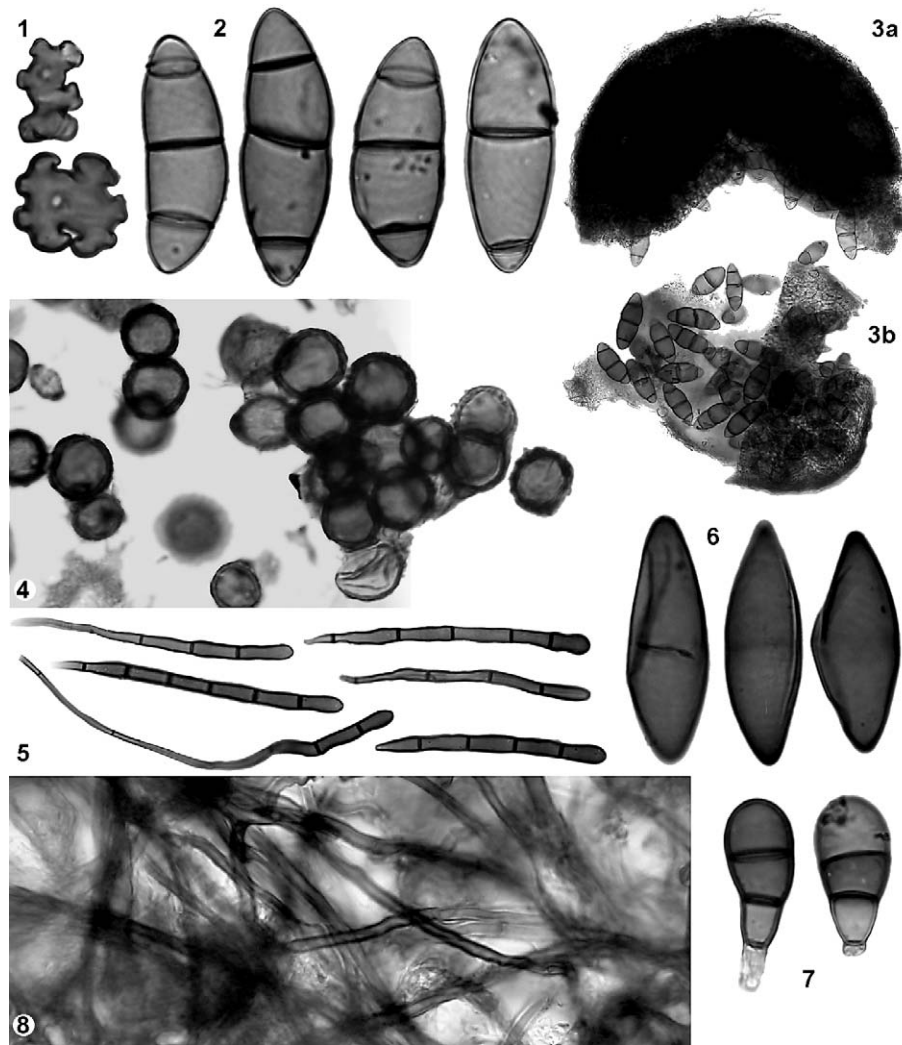**Ascospores** (44−) 49−59 × 16−20 μm, three septate, inequilateral (one side almost straight or even concave),

Fig. 5. AND1 fungal microfossils. (1) Hyphopodia of the fungus *Gaeumannomyces* cf. *caricis* (Type 126; original magnification ×640); (2) Type 810 cf. *Byssothecium alpestris* (Tóth) Boise, ascospores (Boise, 1989; ×640); (3a,b) Broken fruit bodies of the Type 810 fungus, showing ascospores (×160); (4) Type 811 spores (×640); (5) Type 812 conidia or chlamydospores (×320); (6) Type 813 ascospores (×640); (7) Type 814 conidia or chlamydospores (×640); (8) mycelium (×640).

slightly constricted at the septa. Each septum showing a ca. 0.5-µm-wide pore. Two-septate and four-septate spores also occur, but these are rare.

Fruit bodies globose, 150–200 µm in diameter (only broken fruit bodies were observed in pollen slides).

A.2. Type 811 (Fig. 5: 4)

Spores globose, 10–18 (–23) µm in diameter, with roughly textured walls. Often groups of clustered spores were found in the microfossil slides. The origin of Type 811 is unknown (fungus?), but it closely resembles Type 38 (van Geel, 1972), which occurs in NW European raised bog deposits. However, no conclusions could be drawn from the record of Type 38 in those deposits (van Geel, 1978).

A.3. Type 812 (Fig. 5: 5)

Fungal **conidia** or **chlamydospores** transversely (3–) 6–10 (–16) septate, (50–) 120–200 (–250) µm long and 5–8 µm wide, formed at the ends of septate ca 2.5-µm-wide hyphae.

A.4. Type 813 (Fig. 5: 6)

Ascospores one septate, 46–52 × 17–20 µm. Septum often no longer attached to the spore wall. Nonseptate spores were also observed.

A.5. Type 814 (Fig. 5: 7)

Fungal **conidia** or **chlamydospores** transversely three septate, (25–) 31–38 µm long and 13–17 µm wide.
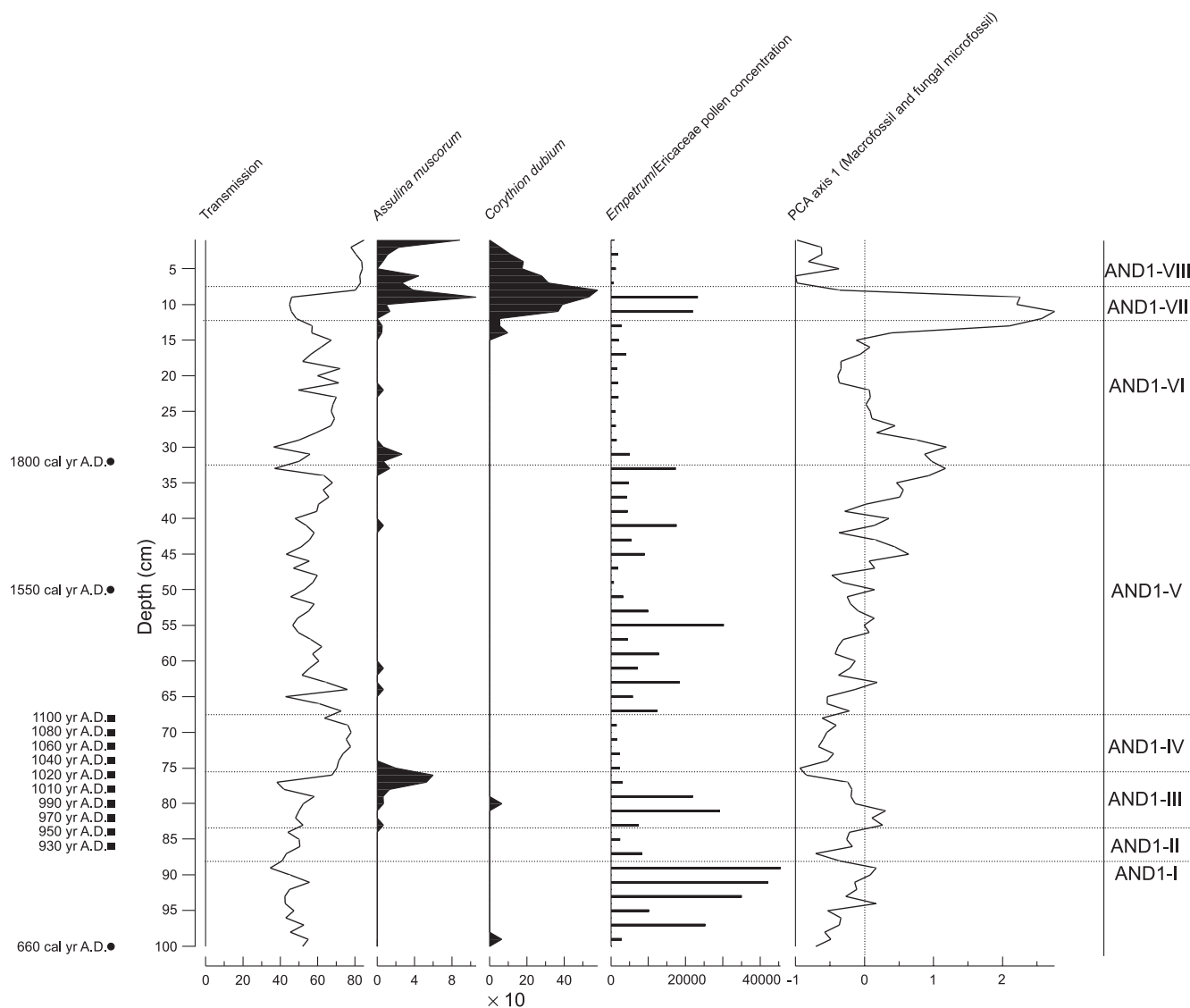
Fig. 6. AND1 composite diagram. Pollen concentrations of *Empetrum*/Ericaceae expressed as grains cm^{-3}, Transmission, *A. muscorum* and *Co. dubium* are percentages. PCA axis 1 sample scores from Fig. 4 plotted versus age/depth.
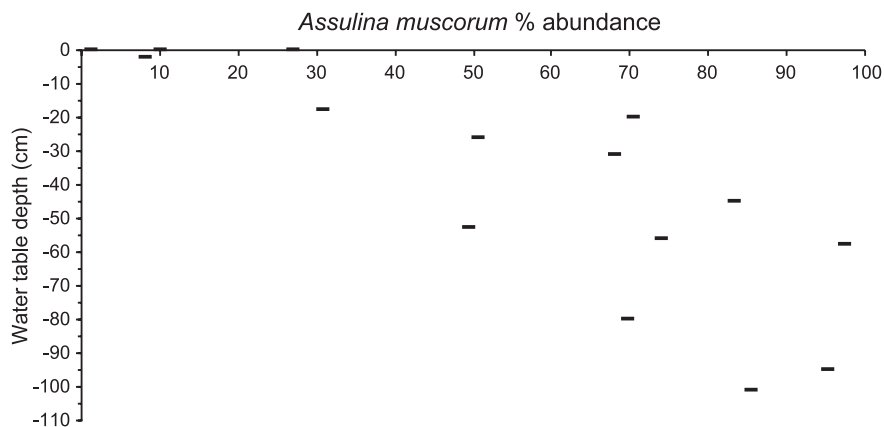

Fig. 7. Depth of water table plotted against the percentage (testate amebae sum of 150) of *A. muscorum* (black rectangles) from 15 sites on the intact peat bog surface (S 54°45′, W 68°19′). Surface samples contained *S. magellanicum* only.

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