Age interpretation of the Wonderkrater spring sediments and vegetation change in the Savanna Biome, Limpopo province, South Africa

Louis Scott[a*], Karin Holmgren[b], A. Siep Talma[c], Stephan Woodborne[c] and John C. Vogel[c]

Spring accumulations are valuable and rare sources for Quaternary pollen analysis and palaeoenvironmental research in South Africa. It is important to optimize their dating, which is sometimes complicated by root contamination. Thirteen new radiocarbon dates are presented from one of the most significant spring pollen sequences on which South African vegetation history is based, namely, from Wonderkrater in the Savanna Biome. Some anomalous measurements were recorded but a new chronology is proposed by excluding samples that were possibly contaminated by younger or older materials. The dating places the pollen-based vegetation history more firmly in a framework of regional and global climate change during the Late Quaternary, thereby making the information more suitable for comparison with other sequences and as vegetation data in global-change modelling.

Introduction

Pollen analysis of 8 m of thermal spring sediments from Wonderkrater (24°25.806′S, 28°44.626′E at *c.* 1110 m altitude) (Fig. 1) gave a unique insight into environmental changes in the Savanna Biome during the Late Quaternary in a region that yields very few potential sources of palaeoclimatic information.[1,2] Correlating regular changes in the pollen record with local and global events has, however, been a problem in view of low dating resolution. Here we provide new radiocarbon dates of the pollen sequence in order to produce a calibrated age model. We compare the sequence of environmental changes at Wonderkrater with the recently generated, continuous high-resolution stalagmite sequences in the nearby Makapansgat Valley (24°8.824′S, 29°10.371′E at *c.*1399 m altitude) that date back to the last glacial period on the basis of uranium series dating.[3,4] The stalagmites indicate regular climatic variability and vegetation change which can also be expected to show up in the Wonderkrater pollen sequence if the two records can be viewed on the same chronological scale. On the basis of anomalies and similarities between the two sets of data, local environmental changes in the region can potentially be more effectively explained. These insights can provide an improved means of comparison with more distant proxy records of global palaeoclimate change, for example, the Vostok ice core record from Antarctica, so that

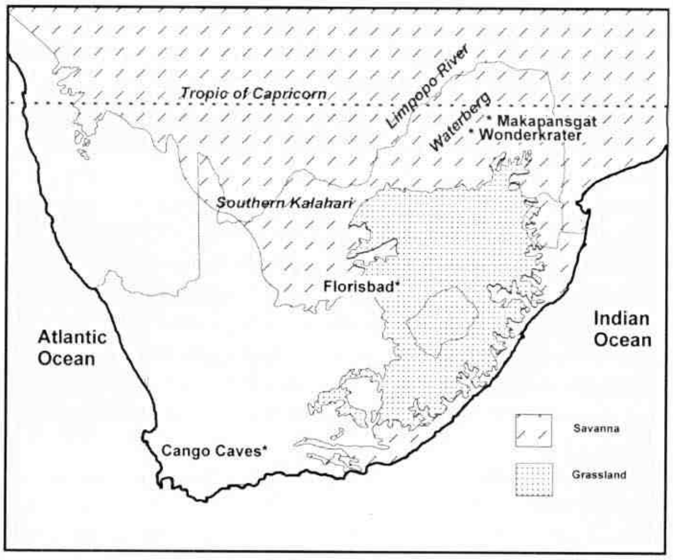

Fig. 1. Locality map.

the results can be applied more effectively in modelling long-term global change.

The Wonderkrater thermal spring site is situated in Low and Rebelo's [5] Mixed Bushveld, which forms part of the Savanna Biome.[6] The pollen record from its black peaty deposits provided the first substantial record of vegetation change in the region.[1,7] Of several boreholes drilled at Wonderkrater using a Hiller corer, boreholes 3 and 4 (B3 and B4) at depths of 1.85 and 8.05 m, respectively, provided partly overlapping sequences. B4 penetrated a 30-cm sand layer at *c.* 4.35 m depth (Fig. 2). Below the sand the section presented dating difficulties. It contained prominent montane forest pollen indicating that *Podocarpus* trees were growing in the vicinity of the spring during its early history. These trees were eventually replaced by indicators of dry woodland. B3 gave an apparently continuous record of at least 14 000 yr BP (uncalibrated age) above the sand horizon that forms its base at *c.* 4. 85 m. The basal one metre of peat corresponds to pollen zone W4.[1] This zone represents pollen from the end of the Last Glacial Maximum with the upland fynbos elements Ericaceae, *Cliffortia* and *Passerina* indicating a vegetation and temperature depression of at least 1000 m and 5–6°C, respectively.[1] This vegetation was gradually replaced by different variations of the current tropical savanna, with Combretaceae and associated woody species including a phase of strong local evaporative conditions with Chenopodiaceae and Amarantaceae (Cheno/Ams) around terminal Pleistocene

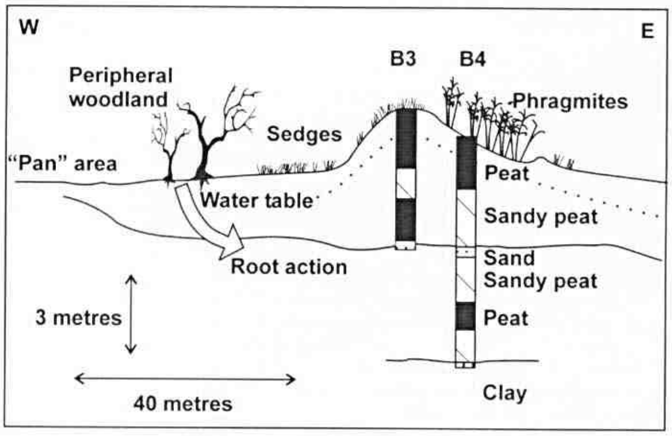

Fig. 2. Schematic west/east section through the Wonderkrater peat accumulation showing the B3 and B4 boreholes and the possible route of root contamination.

[a]Department of Plant Sciences, University of the Free State, P.O. Box 339, Bloemfontein 9300, South Africa.
[b]Department of Physical Geography and Quaternary Geology, Stockholm University, S-106 91 Stockholm, Sweden.
[c]QUADRU, CSIR, P.O. Box 395, Pretoria 0001, South Africa.
*Author for correspondence. E-mail: scottl.sci@mail.uovs.ac.za

times, and arid woodland in the Early Holocene. The Wonderkrater pollen data have been ordinated using principal components analysis (PCA) and the results provided the first Late Quaternary temperature and moisture indices for the region.[2,8]

Previous dating results from Wonderkrater and the problem of contamination

Virtually all previously studied spring deposits in southern Africa have given anomalous radiocarbon dates, so that this complication is not unique to the Wonderkrater sequence. An exception may be the recent study of a Holocene peat from the Florisbad spring (Free State), where a special effort to remove minute rootlets gave more consistent results.[9] In the case of peat from Rietvlei Dam where anomalous dates were measured, minute rootlets were found by microscopic search,[10] suggesting that they might be responsible for the contamination.

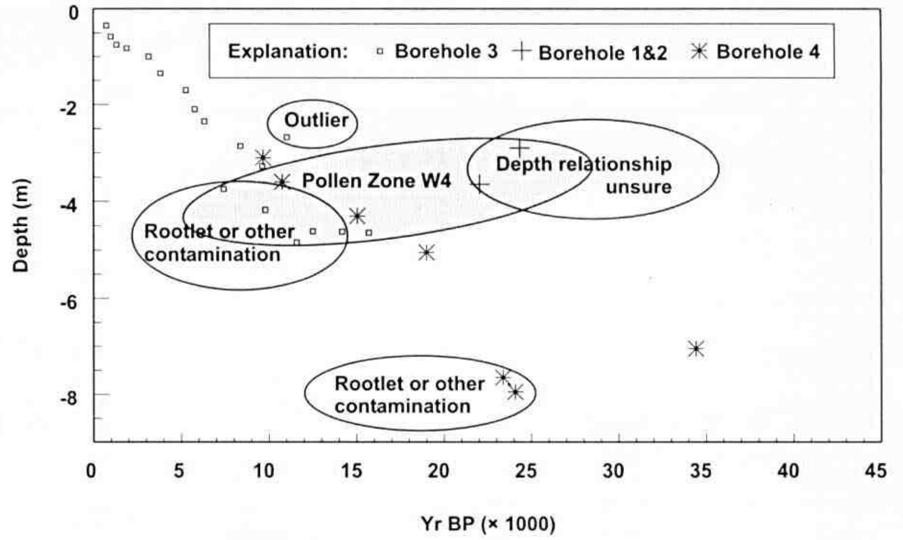

Fig. 3. Plot of radiocarbon dates from cores B1–B4 with depth.

Uncalibrated radiocarbon dates previously obtained in B3 and the deeper B4 core, about 20 m away (Fig. 2), supported our early assumption that B3 was problem-free in terms of younger contamination but that the deeper part of B4 had time/depth discrepancies (Fig. 3).[1,2,11] Exploratory boreholes 1 and 2 (B1 and 2) were cored in 1971 by E.M. van Zinderen Bakker from near a pit with water but their location cannot be identified exactly and therefore their stratigraphic relationship with B3 and 4 is unknown. Their pollen contents and radiocarbon dates are, however, relevant to the assessment of the age of the peat deposits (see discussion below) because they show that the distinct pollen zone W4 represents a time interval stretching as far back as 24 300 yr BP (uncalibrated age).

Root contamination is a likely cause of dates that are apparently too young, since the wet spot created by the spring in relatively dry surroundings attracts denser vegetation with increased root action (Fig. 2). *Phragmitis* and other semi-aquatics in the swamp at Wonderkrater can potentially contribute to younger contamination but these can be seen and removed in the upper peat layer. Currently the spring's circumference consists of trees, including acacias, with deep-penetrating roots. It is likely that a setting with surrounding trees prevailed throughout the history of the accumulation. Over time deep roots could gradually have contaminated old peat with younger carbon. The effect can be expected to be most severe in the oldest part of the deposit that underwent a longer period of ambient modern carbon admixture by root contamination. Mature rootlets in the oldest section are probably indistinguishable from the peat matrix and therefore difficult to remove during pre-treatment for dating. Where tree roots introduce modern carbon into an older organic layer, the relative proportion of modern carbon in the sediment at the time of root growth may have been quite substantial.

Another potential source of contamination of younger material was the use of the Hiller peat sampler that was available to us in the mid-seventies. At the time of coring, however, as many precautions as possible were taken to avoid downward contamination with younger organic material.

Owing to the uncertainties in the deeper Wonderkrater deposits below the sand unit, we did not attempt to generate an age model for B4 at this stage.

Methods

Thirteen new peat samples were selected for radiocarbon dating from stored material of B3 only. The radiocarbon measurements were performed at QUADRU, CSIR, Pretoria, with collaboration from the Groningen radiocarbon laboratory that provided one AMS date (Table 1). Radiocarbon ages from B3 that are considered reliable on the basis of criteria outlined below were calibrated using INTCAL98[12,13] extended to beyond 24 000 kyr[14] with a correction for the southern hemisphere.[15] The resulting ages that were used are the midpoints between the $\pm 2\sigma$ age ranges (Table 2). An age model (Fig. 4) was produced by linear interpolation between these calibrated ages.

Results

The new dating results from B3 are indicated in Table 1 (marked with an asterisk) together with details of previous dates from B1–4.[1,11] All the dates are plotted in Fig. 3. The new measurements from the upper *c*. 2.6 m of B3 show a consistent age/depth trend but below this level there are inconsistencies (Pta-8325, 8327, 1710 and 8475) (Fig. 3). Further, an outlier date of 11 030 yr BP at 260–275 cm (Pta-8323) seems to be 'too old'. These results challenge our earlier suggestion[1,11] that B3 represents a problem-free chronology.

Constructing the age model

To select the most reliable dates, we have assumed that root contamination or downward contamination through the process of coring might be reasons for 'young' dates, and that the relatively 'old' ones that fall in linear order are least influenced, if at all.[1,10] We acknowledge the possibility that the apparently 'old' dates may also have a relatively small level of contamination, and may represent minimum ages. Apart from Pta-8323 (11030 yr BP at 260–275 cm depth), which we discuss below, twelve selected 'old' dates from B3 appear to be suitable (marked + in Table 1). We retain them in order to generate an age model and discard the other 'younger' dates. The calibrated ages of these apparently reliable dates are plotted in Fig. 4. They suggest a peat accumulation rate for B3, which is similar to an overlapping part of B4 that corresponds with the Pleistocene/Holocene transitional phase (Fig. 3). Pollen zones from these levels can be well correlated between the overlapping parts of B3 and B4[1,11] suggesting a consistent accumulation rate in both cores.

Reworking of peat by animal bioturbation, as can happen as a result of aardvark burrowing or hoof action and footpath

Table 1. Radiocarbon dates from boreholes B1–4 at Wonderkrater.

Anal. No.	Bfn No.	Borehole	Depth (cm)	$\delta^{13}C$ (‰ PDB)	Radiocarbon age (yr BP)	±Yr	Pollen zone
Pta-1062	4483	1	375–395	–25.4	22 040	240	W4
Pta-1066	4468	2	280–300	–25.9	24 340	260	W4
Gr-A-17549*+	5538	3	35	–24.2	755	40	W10
Pta-1711+	5554	3	55–60	–24.8	1 000	50	W9
Pta-8311*+	5546	3	75	–24	1 330	60	W9
Pta-8316*+	5555	3	80–85	–23.6	1 910	50	W9
Pta-8310*+	5551	3	100	–22.2	3 160	60	W8
Pta-8312*+	5559	3	135	–23.8	3 830	60	W8
Pta-8336*+	5567	3	170	–25.3	5 280	70	W7
Pta-8345*+	5576	3	210	–24.9	5 790	70	W7
Pta-2311+	5584	3	230–240	–24.6	6 330	75	W6b
Pta-8323*	5595	3	260–275	–24.1	11 030	100	W6b
Pta-1708+	5596	3	280–292	–24.8	8 390	85	W6a
Pta-1709+	5607	3	320–335	–25.2	9 640	80	W5
Pta-8325*	5619	3	367–383	–24.7	7 430	60	W4
Pta-8327*	5630	3	410–425	–25.1	9 800	25	W4
Pta-1710	5641	3	455–470	–24.4	14 180	110	W4
Pta-8474*	5642	3	455–470	–23.7	12 510	120	W4
Pta-8473*+	5639	3	465	–23.7	15 700	190	W4
Pta-8475*	5645	3	485	–24.7	11 580	220	W4
Pta-6270	6521	4	310	–25.2	9 680	90	W5
Pta-6276	6521	4	310	–25.4	8 940	35	W5
Pta-6272	6526	4	360	–26.4	10 760	100	W4
Pta-6285	6526	4	360	–25.8	10 230	30	W4
Pta-2232	6533	4	420–440	–24.5	15 040	100	W4
Pta-2114	6540	4	500–510	–22.8	19 500	175	W2
I-10,128	6560	4	700–710		34 400	1900	W1b
Pta-2249	6566/7	4	760–770	–23.7	23 370	250	W4a/b
Pta-2050	6570	4	790–800	–24.4	25 060	290	W1a

*, New dates; +, dates retained for age model.

Table 2. Calibration of selected radiocarbon dates.

Lab No.	Depth (cm)	^{14}C years BP	Calibrated age
Gr-A-17549	35	755 ± 40	697 (666) 644
Pta-1711	57.5	990 ± 50	953 (913) 748
Pta-8311	75	1330 ± 60	1304 (1253) 1066
Pta-8316	82.5	1910 ± 50	1907 (1822) 1702
Pta-8310	100	3160 ± 60	3461 (3355) 3210
Pta-8312	135	3830 ± 60	4397 (4156) 3982
Pta-8336	170	5280 ± 70	6190 (5987) 5897
Pta-8345	210	5790 ± 70	6690 (6528) 6401
Pta-2311	235	6330 ± 75	7405 (7243) 7002
Pta-1708	286	8390 ± 85	9522 (9419) 9116
Pta-1709	327.5	9640 ± 80	11185 (11080,10935,10869) 10680
Pta-8473	465	15700 ± 190	19127 (18690) 18253

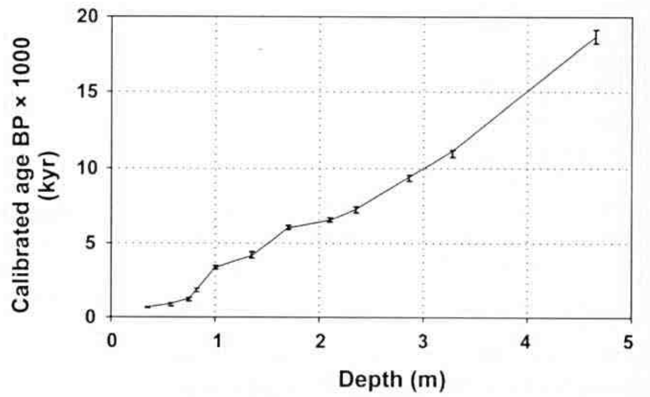

Fig. 4. Calibrated age versus depth plot of selected radiocarbon dates.

erosion, for example, can bring older material to the surface and this might explain the anomaly of Pta-8323. Apparent ageing of peat can, however, also be caused by a change of CO_2 source with low ^{14}C content, via submerged stomata of the aquatic peat-forming vegetation. We obtained a ^{14}C content of 10.2 pmc ^{14}C (water age of 17 000 years) from a nearby artesian well, which apparently represents the same source[16] as the spring water due to its closeness (less than 1 km north of the spring) and identical water chemistry (S. Talma, unpublished data). The ^{13}C content of –24.1‰ of Pta-8323 is, however, not sufficiently different from the rest of the profile (Table 1) to indicate a CO_2 source other than the atmosphere. A decline in pollen of aquatic plants (*c.* 1.5%) and semi-aquatic Cyperaceae (*c.* 16%) within levels 260–275 cm compared to the rest of the sequence (averages *c.* 5% and 27%, respectively; Fig. 5) gives no support for the old-water CO_2 hypothesis.

Environmental history

In order to stand firmly as an independent chronological sequence, the Wonderkrater site will ultimately have to be cored again, re-dated and the pollen re-analysed. The potential of conducting optically stimulated luminescence dating on the sand layers will also help to verify the age model. Meanwhile, our age model is the best approximation to serve as a chronology for this pollen history of the savanna (Fig. 5). Principal components values (PC1 and PC2) for 15 selected pollen indicators are plotted according to this chronology and compared with other climate records in Fig. 6. PC1 and PC2 weights (Fig. 7) show contrasts between significant temperature and moisture indicators[8] that allow them to be applied as moisture and temperature indices in Fig. 6. The indices rely on parallel fluctuations of taxa that reflect temperature and moisture changes and seem to be fairly robust as similar patterns have been recorded

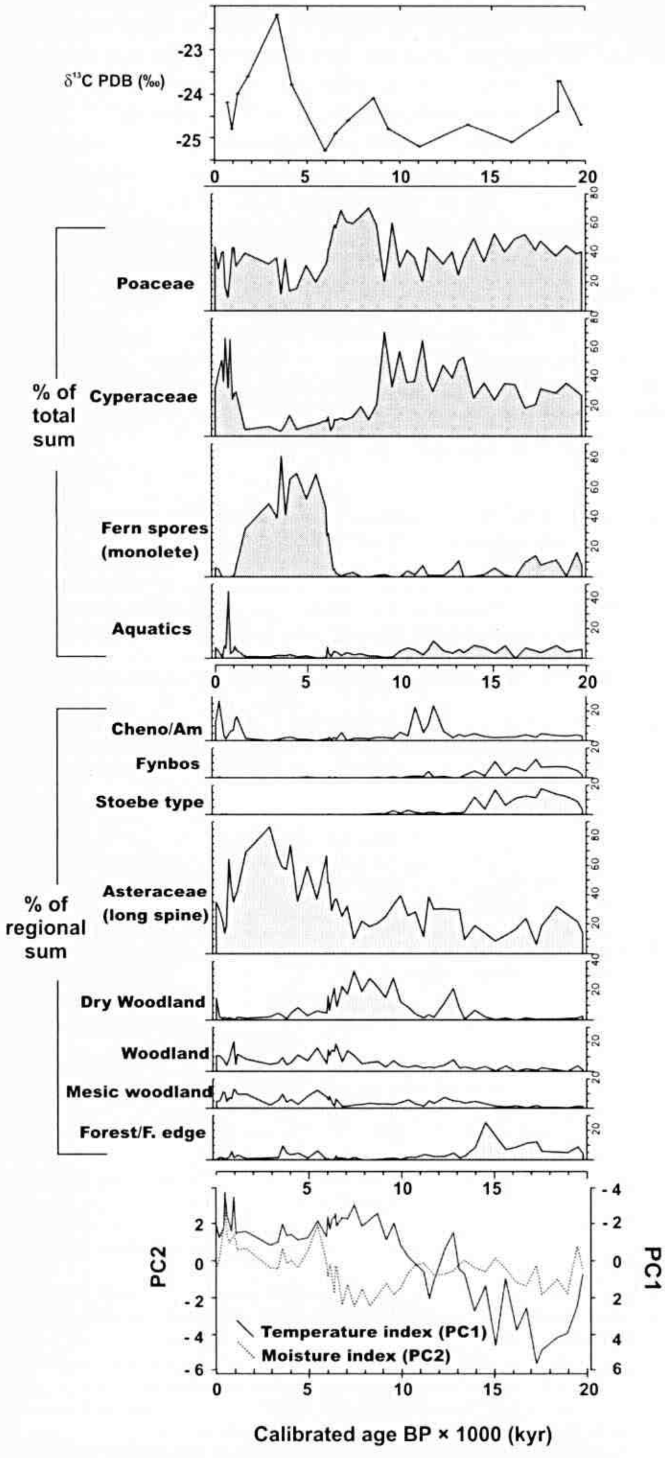

Fig. 5. Pollen diagram, and corresponding temperature, moisture indices, and $\delta^{13}C$ at Wonderkrater. Anomalous radiocarbon dates associated with the stable carbon values have been adjusted to the age model adopted in this paper according to their depths.

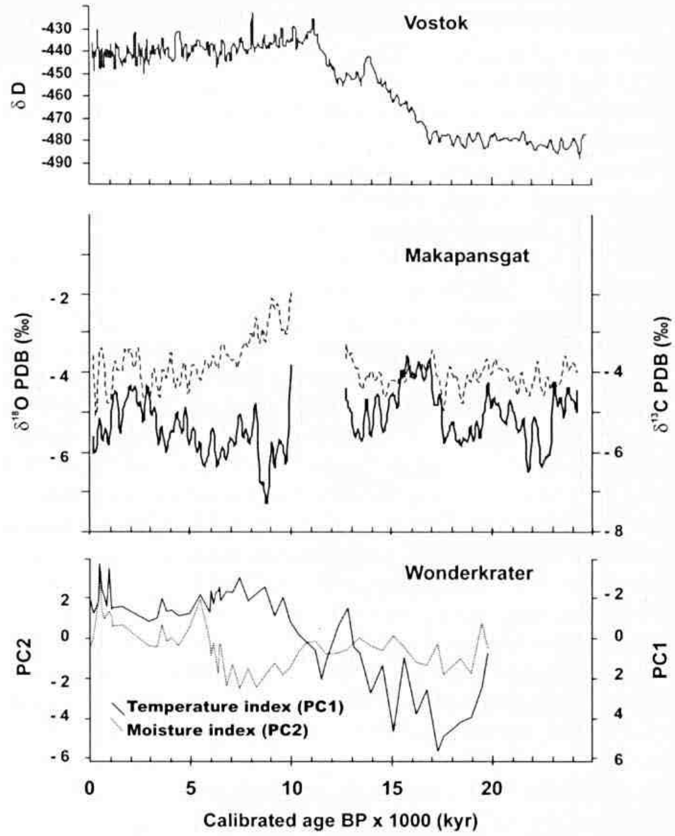

Fig. 6. Wonderkrater temperature and moisture indices compared with the T8 stalagmite record from the Makapansgat Valley[4] and the Vostok ice core record.[18]

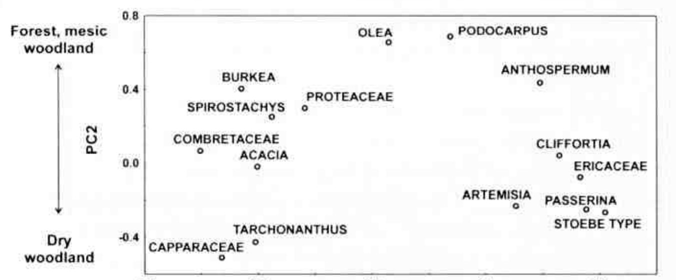

Fig. 7. Principal components analysis weights of 15 selected pollen taxa. The contrast in distribution along the Factor 1 axis was applied in the temperature index and Factor 2 in the moisture index as plotted in Figs 5 and 6.

regionally in other sites.[2,8,17] Temperature change at Wonderkrater closely parallels that of the Vostok ice core,[18] although the main warming events appear to be approximately 1 kyr later in the Wonderkrater record (Fig. 6). The timing of the main temperature and moisture changes in the Wonderkrater sequence is of interest in comparison with the $\delta^{18}O$ and $\delta^{13}C$ data from the nearby Makapansgat Valley stalagmite, which are also expected to reflect past temperature and moisture changes (Fig. 6). Compared to the Vostok and Wonderkrater records, a major discrepancy is noted in the Makapansgat oxygen record, where little contrast is indicated between the Last Glacial Maximum and the Late Holocene, whereas the Early Holocene has high isotope values.[4] In terms of temperature this discrepancy is difficult to explain and may possibly be attributed to unknown environmental factors related to local conditions and oxygen isotope fractionation in the stalagmite.[4] On a millennial scale, however, some of the lower amplitude variations do show similarities with the pollen record. We conclude that although the curves are not similar, they complement each other as different record types influenced by different processes. If these differences can be understood, they promise to shed more light on Quaternary processes in the study area. Details of the isotopic results have been presented in Holmgren *et al.*[4] A comparative interpretation of environmental conditions in terms of the pollen record is presented below.

The Wonderkrater pollen sequences as well as the isotope records of Makapansgat[4] and Cango Caves[19] place the coldest conditions at *c.* 17 kyr. Increasing temperatures are indicated in both the Makapansgat $\delta^{18}O$ and Wonderkrater pollen records at *c.* 13 kyr. This warming at Wonderkrater appears to be coeval with the Younger Dryas in the northern hemisphere but *c.* 1 kyr later than the trend reflected in the Vostok ice core.

From 12.7 to 10.2 kyr a hiatus is found in the Makapansgat speleothem record, whereas the Wonderkrater sequence indicates a return to slightly cooler but evaporative conditions with Chenopodiaceae and Amarantaceae (Cheno/Ams). From about 10.2 kyr both the stalagmite and the pollen records suggest that conditions were becoming drier. However, at 8.5 kyr the $\delta^{13}C$ record at Makapansgat indicates a sudden change to more grassy conditions (higher values). This corresponds to an increase in grass pollen at Wonderkrater. The dryness index for Wonderkrater which is independent of Poaceae (grasses), however, indicates that desiccation continued and intensified (Fig. 5). This may appear to contradict the indicated richness of grass in the region. The associated pollen, however, suggests a relatively open savanna with Kalahari trees, shrubs and dry grassland. The sudden change at *c.* 8.5 kyr at the spring shows the replacement of local swampy Cyperaceae with grass pollen (Fig. 5), probably in part representing a dry-land grass incursion into the wet area while the spring was shrinking.[1] The change to more grassy conditions at Makapansgat can therefore be a result of a similar prominence of dry grass and a decline of mesic woody elements. More rain is therefore not necessarily indicated by increased $\delta^{13}C$ during this interval of the Makapansgat record.

Warmer temperatures according to the Wonderkrater index occurred at roughly 9.5–6 kyr. This trend does not follow the $\delta^{18}O$ curve from Makapansgat closely, although relatively high temperatures for the period are also indicated (Fig. 6). Given the limitations of the oxygen record[4] and the Wonderkrater temperature curve,[2] a close correspondence between them should not be expected.

Cooling is apparent in the Wonderkrater spring sequence after *c.* 6 kyr and temperatures reach their lowest values by *c.* 3 kyr, corresponding to the isotope records of Makapansgat (Fig. 6).[4] Moderate dryness is also indicated at Wonderkrater during this period. A high proportion of fern spores was produced in the spring between *c.* 6 and 2 kyr that must have given the swamp a bracken-like appearance, but the regional vegetation seems to have shown a strong increase of Asteraceae peaking around 2 kyr (Fig. 5). Asteraceae pollen, which does not form part of the temperature index in Fig. 5, has independently been related to slightly cooler conditions at *c.* 3–2 kyr on the basis of the distribution of modern pollen in the region.[1] $\delta^{13}C$ enrichment between 3 and 2 kyr in both the Makapansgat T8 and T7 stalagmites indicates strong grass growth (C_4) and weak tree and small shrub (Asteraceae) growth (C_3).[4,20] This might seem contradictory in view of the strong Asteraceae presence at Wonderkrater. If we assume the Asteraceae spread was regional, affecting also the Makapansgat region, then other C_3 plants such as trees must have declined strongly in favour of grass in order to give the high $\delta^{13}C$ values of the stalagmite. The Wonderkrater pollen sequence supports such a scenario with the low arboreal pollen percentages. The grass proportion in the Wonderkrater pollen sequence is intermediately low but $\delta^{13}C$ values peak at these levels (Fig. 5), indicating that at least some of the plants at the spring must have been derived from C_4 growth. It is therefore likely that conditions were favourable for C_4 grasses, supporting the Makapansgat data.

The sample resolution for the phase between 2 and 3 kyr in the Wonderkrater sequence is low in view of a fast sedimentation rate indicated by our adopted chronology. Ideally, this part should be analysed at closer depth intervals. The low resolution available prevents close correlation with the more detailed and strongly variable isotope records at Makapansgat as well as the Cango Caves.[4,19–21] Sharp oscillations in temperature and moisture conditions have, however, occurred in the last millennium as indicated by variations in pollen types. To investigate the variability in the last 3000 years at Wonderkrater more effectively in relation to the Makapansgat record, it is desirable to re-analyse new core material from the site.

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