

Late Quaternary Paleotemperatures Derived from a Speleothem from Cango Caves, Cape Province, South Africa

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An oxygen isotope temperature record over a large part of the past 30,000 yr has been obtained for the southern Cape Province of South Africa by combining data on the isotopic composition of a stalagmite from a deep cave with that of a confined groundwater aquifer in the same region. Results show that temperatures during the last glacial maximum were on average about 6°C lower than those today, with peaks up to 7°C lower. A detailed analysis of the past 5000 yr suggests multiple fluctuations, with generally lower temperatures (1–2°C) around 4500 and 3000 yr B.P. The carbon isotopic composition of the stalagmite indicates significant vegetation changes between the late Pleistocene and today, and also during the second half of the Holocene. © 1992 University of Washington.

INTRODUCTION

The evidence of late Quaternary climates along the southernmost coast of Africa, essentially the southern part of the Cape Province, is mainly of a circumstantial nature (Butzer, 1984; Deacon *et al.*, 1984; Tyson, 1986). Recently, however, Heaton *et al.* (1986) derived late-glacial temperatures from the dissolved gas content of old artesian water and have shown that between 30,000 and 15,000 years ago temperatures were about 5°C lower than at present.

In this paper we report an isotopic study of a stalagmite from the Cango Cave near Oudtshoorn in the southern Cape Province. Paleotemperatures and some information on the vegetation during most of the last 47,000 years is derived. A preliminary report of this work was presented by Vogel (1983a) and earlier versions of the temperature curve were reviewed by Tyson (1986) and by Deacon and Lancaster (1988).

Isotope Geochemistry of Speleothems

The oxygen isotopic composition of carbonate deposits can, in principle, be used to calculate the temperature at which the calcium carbonate was precipitated. This is because the isotope fractionation that oc-

curs during precipitation from aqueous solution is temperature dependent. There are, however, a number of conditions that need to be fulfilled before meaningful paleotemperatures can be derived from such measurements (Hendy, 1971; Schwarcz, 1986):

- (1) The carbonate precipitate must have been in isotopic equilibrium with the water at the time of formation.
- (2) The oxygen isotopic content of the water must be known.
- (3) No diagenetic alteration of the isotope record must have occurred.
- (4) The deposit must be properly datable.

Among the various types of terrestrial carbonate deposits, speleothems, and particularly stalagmites, have the most promise of fulfilling these requirements (Schwarcz, 1986). In a poorly ventilated cave the release of carbon dioxide from cave drip water would be sufficiently slow to ensure that conditions for equilibrium precipitation would prevail. The cave temperature would also be close to the local average temperature. If the stalagmite, furthermore, is compact and nonporous the likelihood of subsequent isotopic alteration is small. Such speleothems can also be

dated by the radiocarbon and/or ionium methods.

The main obstacle when calculating temperatures from the ^{18}O content of stalagmites is lack of knowledge of the isotopic composition of the water during calcite deposition. The ^{18}O content of present-day cave drip water can readily be measured. Repeated sampling can establish any possible seasonal variations which usually average out toward the mean annual ^{18}O content of precipitation in the area (Goede *et al.*, 1982; Yonge *et al.*, 1985). This mean value can be used to judge whether isotopic equilibrium exists during carbonate precipitation at the *present* time. The ^{18}O value of *past* drip water is, however, usually unknown. It has been estimated by means of a model describing the evaporation-transport-precipitation of moisture in the water cycle (Hendy, 1969; Gascoyne *et al.*, 1980) or calculated from the deuterium content of fluid inclusions in stalagmites (Schwarcz *et al.*, 1976; Schwarcz and Yonge, 1983). In the present study the ^{18}O content of confined and dated groundwater is used to estimate the ^{18}O value of cave drip water in the past.

Temperatures in the deeper parts of caves are generally constant throughout the year and are equal to the mean annual air temperature outside the cave. The low growth rate of most speleothems ensures that a single sample of ca. 20 mg CaCO_3 covers a few decades of precipitation rather than years. The derived temperature will then be sufficiently smoothed to show only decadal variations.

Preservation of the isotope record can be expected when impermeable deposits with large crystals are present. In addition, consistency between two dating techniques will indicate absence of leaching or secondary deposition. For ease of dating and stratigraphic control, stalagmites with discernible flat tops are most suitable.

The ^{13}C content of carbonate deposits is more variable than the ^{18}O content. This reflects the solution processes by which

soil CO_2 dissolves soil carbonate to form bicarbonate dissolved in soil water and the subsequent precipitation of carbonate therefrom in the cave (Hendy, 1971; Mook, 1980). In semitropical areas where a significant C-4 grass component exists in the biomass (Vogel *et al.*, 1978), this will tend to increase the ^{13}C content of the bicarbonate dissolved in the drip water and consequently in the carbonate deposit itself (Talma *et al.*, 1974).

METHODOLOGY

Cango Stalagmite V3

The Cango Caves (22°13'E, 33°23'S) form a well-known cave system (Burman, 1958) in the foothills of the Swartberg Mountains near Oudtshoorn in the south of the Cape Province, South Africa (Fig. 1). The caves are located in the limestones of the Matjies River Formation which form part of the late Precambrian Cango Group (King, 1952). The cave system is some 3 km in extent and consists of three discrete sections.

The stalagmite in question (V3) was obtained from near the end of Cango II, about 1100 m from the opening. At this point the air temperature is a constant 17.5°C and the relative humidity greater than 95%. The specimen was 2.7 m tall with a diameter ranging from 8 cm at the top to 20 cm at the base. It was obviously still growing when removed.

The stalagmite was removed from the cave in sections. Each section was sawed lengthwise; one half was sliced to obtain samples for dating, while the other half was used for stable isotope sampling. In cross-section it was evident that the stalagmite had grown with a relatively flat top, 4 to 8 cm wide, throughout its development, thereby enabling sampling under good stratigraphic control. The stalagmite consists of large, compact calcite crystals which are pure white near the top and become pale brown farther down. No signs of resolution or diagenesis are noticeable anywhere on this specimen. Microscopic ex-

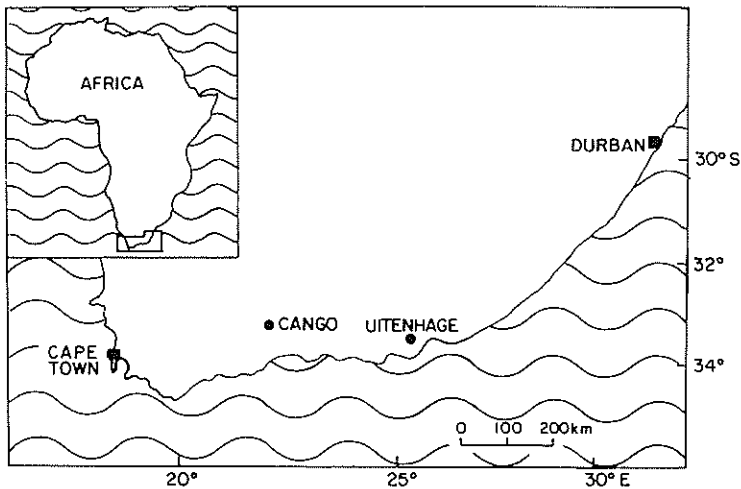


FIG. 1. Map showing location of Cango Caves and the Uitenhage artesian aquifer.

amination did not reveal any cavities likely to contain fluid-inclusion water.

Dating

Twenty-three samples were taken along the axis for ^{14}C and ionium dating. In this manner growth rates were obtained and the major features of the relationship between the two techniques could be demonstrated (Vogel, 1983b). Calculation of the ionium (^{230}Th) ages presented no problems, for very little detrital ^{232}Th was present. Radiocarbon ages were calculated after correction for ^{13}C fractionation and subtraction of 1450 yr to accommodate for the "hard water effect" in the cave drip water. This offset was obtained by extrapolating the distance- ^{14}C age curve to the tip of the stalagmite (Vogel, 1983b). The assumption that the top of the stalagmite is of zero age is valid, since (a) water was still dripping on the stalagmite when it was removed and (b) the ionium dates do, in fact, extrapolate to zero.

The dates indicate a depositional break (at 951 mm from the tip) between 13,800 and 5000 yr B.P. There is no evidence of resolution or any other discontinuity at that point other than a slight change in color from light brown below to pure white above. We have no explanation for this hi-

atus: it could be either a local or a regional lack of cave drip water supply.

The growth rate of the stalagmite was 0.15 mm/yr during the Holocene and 0.06 mm/yr for the part older than 14,000 yr B.P. These are quite typical rates for temperate areas (Harmon *et al.*, 1975).

There are major discrepancies between ^{14}C and ionium dates from 22,000 to 14,000 yr B.P. and from 35,000 to 28,000 yr B.P. (Vogel, 1983b). In view of the general use of the radiocarbon chronology for events during the last 50,000 yr, all dates in this paper are reported in (uncalibrated) radiocarbon years B.P.

Stable Isotope Measurements

Sampling for ^{13}C and ^{18}O measurement was done by drilling 20- to 30-mg samples with a 4-mm drill bit along the main axis connecting the centers of the flat tops. The sampling strategy for the Holocene part of the stalagmite was to obtain at least one sample per century and to resample and interpolate any ^{18}O change corresponding to a temperature change of more than 1°C . On the lower part of the stalagmite the sample intervals were longer and the aim was to follow any observed isotopic variations.

The McCrea (1950) method was used to prepare CO_2 for isotopic measurement, us-

ing 95% phosphoric acid at 25.0°C and allowing the reaction to complete overnight. Initially measurements were done with a Varian GD150 mass spectrometer with precisions in the order of 0.15‰. Later measurements were done with a VG SIRA 24 instrument capable of a long-term precision of 0.03‰. NBS 19 was used as reference standard with a value of $\delta^{13}\text{C} = +1.93\text{‰}$ and $\delta^{18}\text{O} = -2.20\text{‰}$ wrt PDB.

Measurements within 2 mm of each other were considered to be duplicates and were combined into averages. In this manner 250 measurements were used to yield a set of 178 data points. Outliers were identified and could be either confirmed or eliminated. With this procedure most of the isotopic variations shown could be mapped out although some outliers are still evident.

Temperature Calculation

Cave paleotemperatures were calculated from the ^{18}O content of the stalagmite, δ_c , using the Craig (1965) expression:

$$t = 16.9 - 4.2 (\delta_c - \delta_w) + 0.13 (\delta_c - \delta_w)^2 \quad (1)$$

Here δ_w is the delta value of the drip water with respect to the same reference as δ_c . Conversion from SMOW to PDB is accomplished by adding 0.22‰ (Craig, 1961).

The ^{18}O content of drip water in the *past* was obtained by comparison with groundwater from the Uitenhage artesian aquifer.

This aquifer is located near the coast 350 km east of Congo Caves (Fig. 1) and is subject to the same all-season rainfall distribution pattern. At this location groundwater was sampled over a distance of 22 km and regular aging (^{14}C) of the water down-dip was observed (Talma *et al.*, 1984). The ^{18}O content of the water indicated a lower ^{18}O level during the last glaciation (here older than 16,000 yr B.P.) by an amount of 0.94‰ (Heaton *et al.*, 1986). It seems reasonable to assume that the changes in the ^{18}O content of the recharge water are regional phenomena and that they would also have occurred in the Congo Cave area. This pattern of ^{18}O change with time (Fig. 2) was used to estimate the ^{18}O content of paleo-drip water back to 30,000 yr B.P. and for calculation of paleotemperatures with Eq. (1). Drip water was collected near the location of the stalagmite on six occasions between 1978 and 1983. Its ^{18}O content varied between -5.77 and -5.18‰ SMOW, averaging -5.44‰ , which value is accepted as representing present-day cave drip water. Since there is no basis on which estimates could be made for the older period of the stalagmite (30,000 to 47,000 yr B.P.), no paleotemperatures older than 30,000 yr B.P. were calculated.

A tritium measurement of one of the cave drip water samples has shown it to be tritium-free, indicating that the drip-water represents pre-1954 rain recharge. This significant delay implies that short-term isoto-

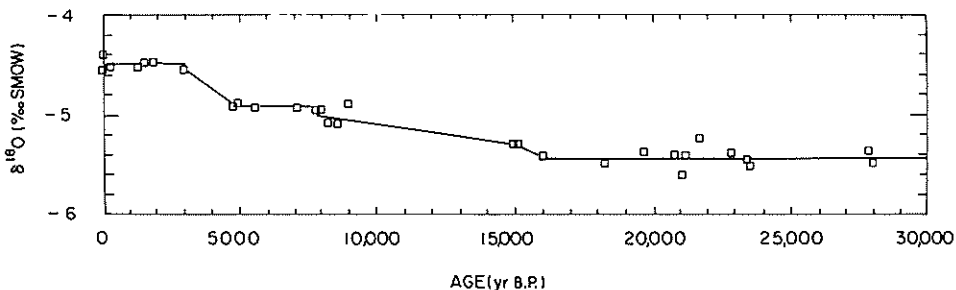


FIG. 2. ^{18}O content of artesian groundwater of different ages from the Uitenhage artesian aquifer (Heaton *et al.*, 1986). The ^{18}O values assumed for the drip water in Congo Caves are 0.95‰ lower than these groundwater values, based on the difference between present-day drip water and the youngest groundwater.

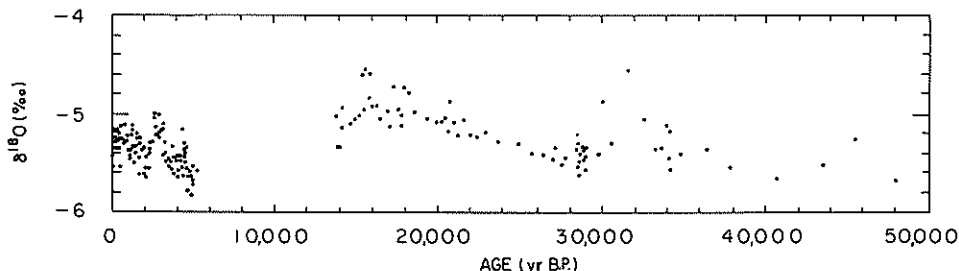


FIG. 3. Variation of the ^{18}O content (relative to PDB) of the Congo stalagmite with age. The absence of data between 5000 and 13,800 yr B.P. is due to the absence of carbonate precipitation during that period.

pic variations in the rainfall can be expected to have been smoothed out before the water enters the cave.

RESULTS

Isotopic Data

The ^{18}O data of this stalagmite do not show much systematic change between the glacial and postglacial periods (Fig. 3). However, calculation of the carbonate deposition temperatures with the aid of the ^{18}O estimates of drip water, as described above, does indicate a highly regular temperature pattern in the past (Fig. 4) consisting essentially of more or less constant temperatures during the past 5000 yr and temperatures 4–7°C lower from 30,000 to 13,800 yr B.P.

In more detail, a slow temperature decrease is evident from 30,000 yr B.P. toward minimum temperature values between 19,000 and 17,000 yr B.P. Thereafter the temperature increased up to 13,800 yr

B.P. when stalagmite growth ceased. On resumption of growth at 5000 yr B.P. the temperature varied essentially within +1° and –2°C relative to present-day temperatures (Fig. 5), with generally lower values between 5000 and 2500 yr B.P. and slightly higher values around 2000 yr B.P.

The ^{13}C variation shows a fairly uniform shift from values near –11‰ PDB at 47,000 yr B.P., increasing to –5‰ during the period 5000 to 2000 yr B.P., and thereafter decreasing to the present-day value near –7‰ (Fig. 6).

Control on Equilibrium Precipitation

Successful temperature calculation using Eq. (1) requires that carbonate deposition was in isotopic equilibrium with drip water, i.e., that no kinetic fractionation was evident during precipitation. This usually requires that CO_2 release from the (carbonate) oversaturated drip water is sufficiently slow. This will generally be the case in a poorly ventilated cave where the CO_2 con-

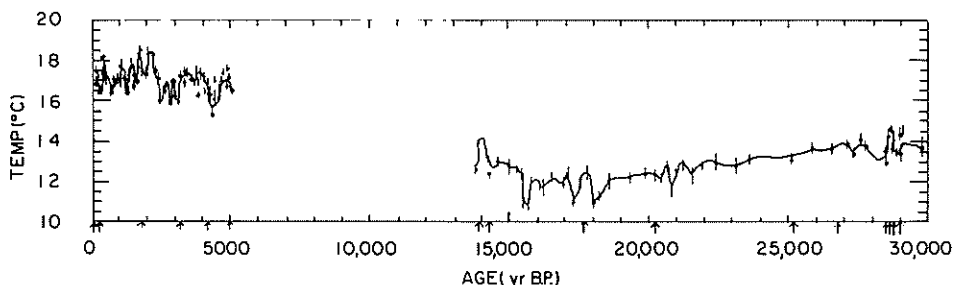


FIG. 4. Derived deposition temperatures of the Congo stalagmite up to 30,000 yr B.P. The solid line is a calculated spline curve. The arrows below the frame indicate the ages of samples taken for dating.

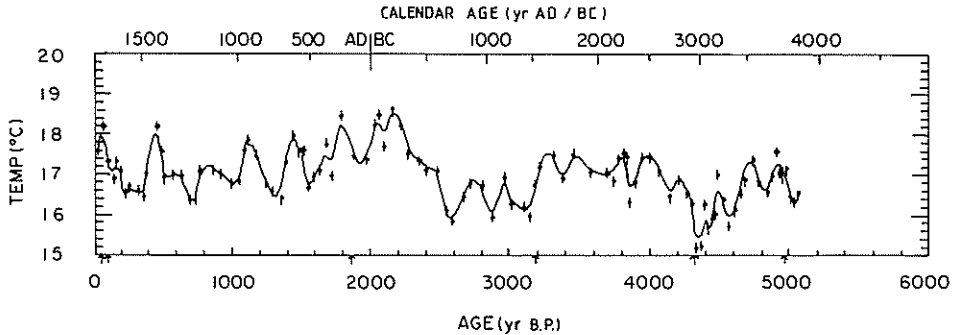


FIG. 5. Late Holocene section of the temperature curve. The solid line is a calculated spline curve. The arrows below the frame indicate the ages of samples taken for dating.

tent of the cave air will be close to the partial CO_2 pressure in the drip water. In Cango Cave II a favorable situation in this respect probably existed before it was discovered and opened in the mid 1970s and its ventilation thereby improved.

Hendy (1969, 1971) proposed a procedure to check whether kinetic effects dominate during calcite precipitation. It involves measuring ^{18}O and ^{13}C along a growth line on top of the stalagmite. He showed that nonequilibrium precipitation of carbonate affects both isotopes, resulting in parallel isotope enrichment of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in the direction of water flow. Absence of such a correlation is therefore an indication that isotopic equilibrium between carbonate and drip water existed and Eq. (1) is valid.

Such measurements were done at 860 and 2400 mm distance from the tip. These two positions were chosen to represent the typical climatic regimes of both the Ho-

locene and the Pleistocene. Samples were taken from the stalagmite tops at those positions and then progressively down the sides of the stalagmite in the direction of water flow as judged from the growth lines in cross-section.

In both sets of measurements the relatively flat tops and the steeply sloping flanks of the stalagmite show significantly different precipitation regimes (Fig. 7). On the tops (respectively, 30 and 47 mm in diameter) $\delta^{18}\text{O}$ varies by not more than 0.3‰ while $\delta^{13}\text{C}$ is virtually constant. Along the flanks of the stalagmite, $\delta^{18}\text{O}$ increases up to 1.4‰ in the direction of water flow downward and correlates with an increase in $\delta^{13}\text{C}$ (Fig. 7). The two sample sets are very similar in this respect.

The absence of correlation on the flat tops indicates that there was no kinetic fractionation during carbonate formation there. It is likely that the water film will be much thicker and the release of CO_2 there-

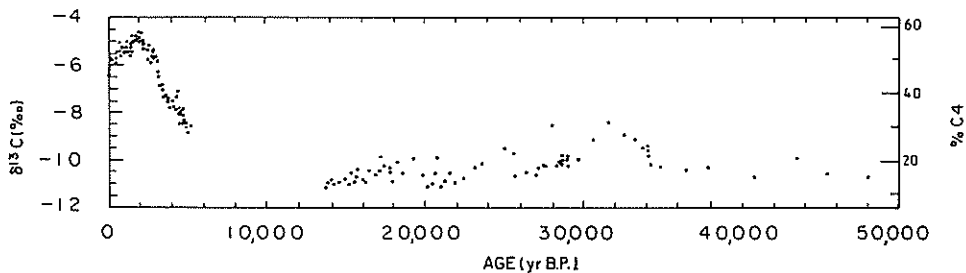


FIG. 6. ^{13}C content of the entire stalagmite. The presumed change of C-4 vegetation is indicated on the right axis.

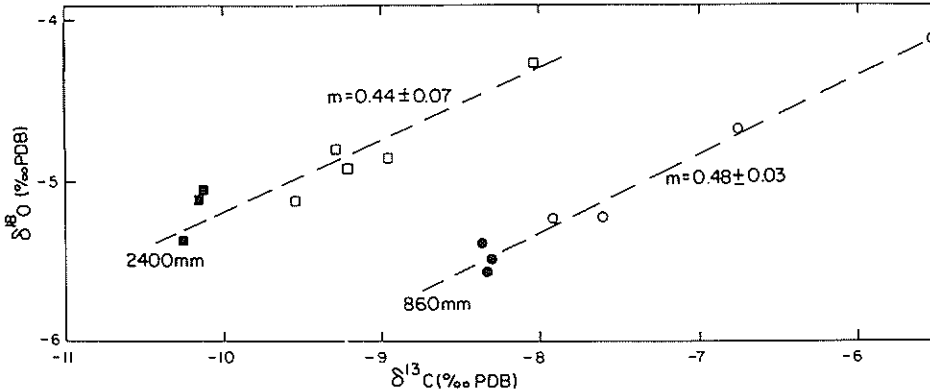


FIG. 7. The relation between carbon and oxygen isotope content on two contemporaneous growth layers at center point heights of 860 and 2400 mm. Solid points indicate samples from the flat tops and open points those from the flanks of the stalagmite. The parallel enrichment of both isotopes along the flanks indicates kinetic fractionation during precipitation.

fore much slower (Dreybrodt, 1981) such as to ensure that isotopic equilibrium exists between carbonate in the liquid and solid phases. Samples taken from this deposition region should therefore produce reliable paleotemperature data. In contrast, isotopic fractionation does occur during carbonate precipitation along the flanks of the stalagmite. In both cases the ^{18}O enrichment is approximately 0.47 times that of ^{13}C (Fig. 7) and indicates kinetic fractionation similar to that produced experimentally (Fantidis and Ehhalt, 1970). This enrichment can be ascribed to the rapid release of carbon dioxide from the thin water layer on the flanks of the stalagmite. Evidently, samples collected from the outsides of the stalagmite are not useful for temperature determination.

The actual temperature measured in the cave (17.5°C) is quite close to the 17.7°C calculated from the oxygen isotopic composition of calcite from the top of the stalagmite and the present-day cave drip water. This supports the conclusion that Eq. (1) is valid here and has also been so in the past.

DISCUSSION

Paleotemperature Record from 30,000 yr B.P. to the Present

It is fortunate that data for the ^{18}O content of water in the area for the last 30,000

yr are available in the form of groundwater from the Uitenhage aquifer. This obviates the necessity to use atmospheric models to derive the ^{18}O content of cave drip water in the past (Hendy, 1969; Gascoyne *et al.*, 1980). The present data provide a useful confirmation of, and supply much more detail than, the temperatures that were obtained from these artesian waters by measuring dissolved gas concentrations (Heaton *et al.*, 1986). Micromammalian and sedimentological evidence in the same area also suggest significantly cooler temperatures for late-glacial times (Partridge *et al.*, 1990), although not with the time resolution and the detail available in the present work. The occurrence of occasional minimum temperature values is notable (Fig. 8) and comparable with the short-term variations recorded in the Holocene (Fig. 5). The establishment of these short-term variations was possible due to the excellent resolution and good preservation provided by this specimen.

Given the small ^{18}O variation in the stalagmite, the temperature calculation depends strongly on the ^{18}O content of the cave drip water which is here derived by comparison with that of the groundwater. Because of the nature of the groundwater aquifer (fractured rock) the ^{18}O variations in groundwater are averaged over several

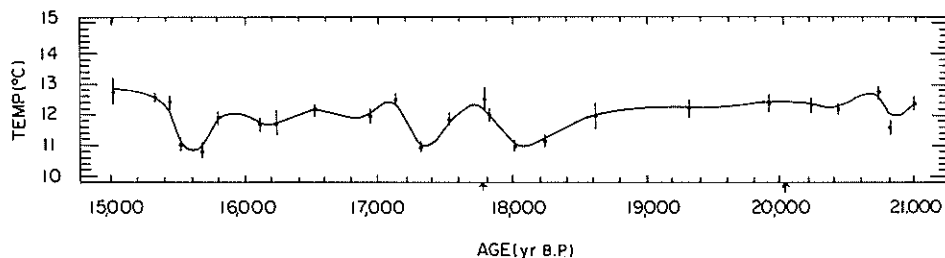


FIG. 8. Temperature curve during the last glacial maximum indicating the minor variations evident during that time. The arrows below the frame indicate the ages of samples taken for dating.

centuries and short-term variations within that time span will not show up. If they were to have occurred, their presence could significantly alter the fine scale features of the Holocene temperature pattern of Figure 5.

There is no explicit independent evidence for the Little Ice Age or some similar event on this part of the continent which could be used for comparison with our curve. The Vostok ice core curve from West Antarctica does not exhibit temperature variations larger than 0.3°C during the Holocene (Jouzel *et al.*, 1987). The worldwide temperature rise during the last 100 yr (Hansen and Lebedeff, 1987) is indeed exhibited in the present curve and suggests that at least the direction of temperature change of our curve is correct. The finer detail of the Holocene temperature curve presented here should therefore be accepted with some reservation until it can be confirmed by other means.

Precise Dating of Paleotemperature Events

The time scale used in this paper is based on ^{14}C measurements as indicated in Figures 4 and 5, with suitable interpolations for individual sample points. It is known that the ^{14}C time scale shows considerable systematic deviations; for example, at 4000 B.C. ^{14}C ages are too young by some 700 yr (Suess, 1978). Comparison with ionium dates on the present stalagmite have shown that radiocarbon dates deviate by several thousand years at various times during the

late Pleistocene (Vogel, 1983b). Recent confirmation of this effect has been provided by the dating of coral cores in Barbados (Bard *et al.*, 1990). Because radiocarbon dates form the basis for the dating of most paleoenvironmental features since 40,000 yr B.P., it has become custom to use the radiocarbon chronology for this time period and express ages as yr B.P. Suitable adjustments will have to be made where results from the present data set are to be compared with events dated by other means (Stuiver and Kra, 1986). For the Holocene temperature curve the calibrated time scale in A.D./B.C. is indicated in Figure 5.

Vegetation Changes since 47,000 yr B.P.

The ^{13}C variation with age of this stalagmite shows a regular pattern (Fig. 6). The glacial-age values are all low compared with those of the Holocene; the lowest values are recorded between 20,000 and 14,000 yr B.P. which corresponds to the minimum temperatures derived from the ^{18}O data (Fig. 4). A local ^{13}C peak occurs at 32,000 yr B.P. Within the Holocene there is a gradual increase from -9‰ at 5000 yr B.P. to a maximum of -4.9‰ at 2000 yr B.P., thereafter dropping to the present-day value of -6.4‰ .

The very regular ^{13}C variation of this stalagmite tempts an environmental explanation. As in many semi-arid regions, the main cause of ^{13}C variation in the environment is the extent of C-4 grass presence in the local vegetation (Talma and Netterberg,

1983; van der Merwe and Vogel, 1984). At present the mountainous area in which the Cango Caves are located is covered with South Rhenosterveld vegetation (Moll *et al.*, 1984), the cover of which consists of 50% grass containing about 80% C-4 grass types (Cowling, 1983a,b). In this respect it is a marginal area sensitive to environmental change.

The influence which the ^{13}C content of plant cover could have on that of the soil water formed therefrom, and hence on the ^{13}C content of calcite precipitated in the underlying caves, can be estimated. The appropriate model for this particular area is the *open* solution model where the three phases, CO_2 gas, water, and limestone are assumed to be in intimate contact and bicarbonate forms in the soil water in isotopic equilibrium with the soil CO_2 . The ^{13}C content of the dissolved bicarbonate, and subsequently that of the calcite precipitated, will be solely determined by the isotopic fractionation factors between the gaseous CO_2 and the other carbon species (Emrich *et al.*, 1970). In a uniquely C-3 environment the ^{13}C content of the calcite will be -12.8‰ PDB and in a pure C-4 area it will be $+1.2\text{‰}$.

If the recharge area of the cave drip water were to have 40% C-4 plant cover, as suggested by the survey of Cowling (1983a), then the mean ^{13}C content of the soil CO_2 will be -17‰ , taking in consideration that there is an enrichment of about -3‰ in the soil atmosphere (Dörr and Münnich, 1980). This is confirmed by four soil $^{13}\text{CO}_2$ values between -14.8 and -18.6‰ obtained from the same vegetation zone nearby (A. S. Talma, unpublished data). Calcite deposited from soil water formed by the open system model described above would then have a ^{13}C value of -7‰ PDB, which is close to the -6.4‰ found on the top of the stalagmite (Fig. 6). The proposed model then appears to be in reasonable accord with the botanical data. It is therefore suggested that the ^{13}C content of this stalagmite can be used as indicator of the C-4/C-3

status of vegetation cover in the area (Fig. 6). The minimum values near the last glacial maximum would then correspond to nearly complete C-3 cover, and the ^{13}C maximum near 2000 yr B.P. (Fig. 6) would be indicative of a slightly greater C-4 grass cover in this area than at present.

The environmental significance of C-4 encroachment has been postulated by Vogel *et al.* (1978) to be due to higher mean temperatures during the (wet) growing season. The lower ^{13}C content of the stalagmite during the last glaciation is therefore consistent with a lower environmental temperature throughout the period and having minimum values at about 17,000 yr B.P.; this agrees with the ^{18}O -derived temperature curve of Figure 4. However, on this basis, the slow increase of ^{13}C from 5000 yr B.P. toward 2000 yr B.P. does not correspond with the fairly constant ^{18}O derived temperature for the same period (Fig. 5). A way to reconcile the ^{13}C data with the temperature curve is to conclude that at 5000 yr B.P. the seasonality of the rainfall tended more toward winter rainfall than the present all-season pattern in the area. At present no other proxy data are available to confirm or reject this hypothesis.

CONCLUSIONS

The 2.7-m stalagmite from Cango Cave has yielded a high-resolution record of temperatures since 30,000 yr B.P. It shows minimum temperatures $5\text{--}7^\circ\text{C}$ lower than present during the period 18,500 to 15,500 yr B.P. An approximately constant temperature, varying only within $+1^\circ$ and -2°C was derived for the period from 5000 yr B.P. to the present.

Measurement of ^{13}C in the stalagmite suggests that from 47,000 to 13,000 yr B.P. little C-4 grass was present in the area. From 5000 yr B.P. onward, considerable C-4 grass invasion took place at a slow rate, reaching an optimum at 2000 yr B.P.

The derived paleotemperature curve is unique in its timespan and high time reso-

lution. No conflicting data are presently known.

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