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Dedicated to professor Gh. Marcu at his 80th anniversary

ACCELERATOR MASS SPECTROMETRY RADIOCARBON DATING OF AN OLD TROPICAL TREE: PRELIMINARY REPORT 2. CALIBRATED RESULTS

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ABSTRACT. The calibration of radiocarbon dates of 11 samples collected from Grootboom, the world's largest African baobab, is presented and discussed. The 1-σ calibrated calendar age of the oldest sample was found to be 1275 ± 50 yr. Hence, Grootboom becomes the first known millenarian angiosperm tree. The acquired results also suggest that morphologically Grootboom was a multiple tree with five fused stems, but genetically it was a single individual. The age of the extreme lateral samples indicates that Grootboom almost ceased growing over the past 500–600 yr. This could be ascribed to climate changes in Central Southern Africa, i.e. a shift towards conditions of prolonged drought.
Several additional samples are under investigation.

KEY WORDS: radiocarbon dating, AMS, tropical trees, age determination, dendrochronology, dendroclimatology.

Part one presented the AMS radiocarbon dating results of 11 samples collected from Grootboom, the world's largest African baobab, which had collapsed recently in Namibia [1].

Part two is dedicated to calibration of radiocarbon dates to calendar ages and to the discussion and interpretation of the resulting age values.

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EXPERIMENTAL SECTION

Calibration. The calculation of the radiocarbon age (^{14}C age) of a sample assumes that the rate of production of ^{14}C and consequently the specific activity/ concentration of the ^{14}C in the atmospheric CO_2 is constant. This assumption is now known to be incorrect, meaning that radiocarbon years are not equivalent to calendar years. Long-term variations in the rate of production correspond to fluctuations in the strength of the Earth's magnetic field. Short-term variations, i.e. "wiggles," are known as the de Vries effect and may be related to variations in sunspot activity.

Radiocarbon ages are always reported as yr BP (before present, where 0 BP = AD 1950), assuming that the atmospheric ^{14}C concentration has always been the same as it was in AD 1950 and that the half-life of ^{14}C is T = 5568 yr (Libby half-life). Consequently, a calibration dataset is necessary to convert uncalibrated conventional radiocarbon dates/ages into calibrated calendar ages. Calibration curves also include the correction factor for conversion to the Cambridge half-life (T = 5730 yr). Calibrated ages are reported as calBP, calBC or calAD, as they are expressed in calendar yr BP, calendar yr BC or calendar yr AD.

Practically, calibration programs calculate, via a calibration dataset, probability distributions of the calibrated calendar age for a certain radiocarbon age (with a certain standard deviation). Probabilities are ranked and summed to find the 68.3% (1-σ; one sigma) and 95.4% (2-σ; two sigma) confidence intervals and the relative areas under the probability curves for the two standard intervals. Each 1-σ or 2-σ probability distribution corresponds, by the selected areas, to one or several ranges of calendar years.

The radiocarbon ages of samples were calibrated with the OxCal version 3.10 for Windows software/program [2-6] and also with the CALIB version 5.0 software/program [7-9], using the atmospheric data from Reimer et al., i. e. the IntCal04 terrestrial calibration dataset [10]. For one sample (No. 11), the atmospheric data from McCormac et al., i.e. the SHCal04 calibration dataset [11] was used .

All calibrated calendar ages and the corresponding errors were rounded to the nearest 5 yr (excepting the calAD ages calculated with the CALIB program, which were rounded to the nearest year).

Table 1.

Calibrated age values of the samples (with the OxCal v.3.1 program)

No. sample	Code sample	^{14}C age [error] (^{14}C yr BP)	Calibration dataset	CalAD age (cal yr AD)		Mean calBP age [error] (cal yr BP)	Age of sample (cal yr in 2005)
				1-σ range(s) [probability]	2-σ range(s) [probability]		
1	LT-C	1255 [± 35]	IntCal04	**680-780 [68.2%]**	670-870 [95.4%]	1220 [± 50]	1275
2	WB-1	360 [± 30]	IntCal04	**1460-1530 [39.0%]** 1570-1630 [29.2 %]	1450-1640 [95.4%]	455 [± 35]	510
3	WB-3	370 [± 20]	IntCal04	**1450-1520 [51.0%]** 1600-1620 [17.2%]	1450-1530 [62.4%] 1550-1630 [33.0%]	465 [± 35]	520
4	WB-4	1045 [± 20]	IntCal04	**990-1020 [68.2%]**	900-920 [1.5%] 970-1030 [93.9%]	945 [± 15]	1000
5	LAS+1	555 [± 25]	IntCal04	1325-1345 [26.4%] **1390-1420 [41.8 %]**	1310-1360 [42.2%] 1380-1430 [53.2%]	545 [± 15]	600
6	LAS	440 [± 25]	IntCal04	**1430-1460 [68.2%]**	1420-1485 [95.4%]	505 [± 15]	560
7	TT-000	865 [± 20]	IntCal04	**1165-1210 [68.2%]**	1050-1080 [4.6%] 1150-1230 [90.8%]	765 [± 25]	820
8	TT-100	1090 [± 55]	IntCal04	**890-1020 [68.2%]**	780-1030 [95.4%]	995 [± 65]	1050
9	TT-220	530 [± 45]	IntCal04	1320-1350 [13.3%] **1390-1440 [54.9%]**	1300-1370 [32.6%] 1380-1450 [62.8%]	535 [± 25]	590
10	TT-270	480 [± 20]	IntCal04	**1420-1440 [68.2%]**	1415-1450 [95.4%]	520 [± 10]	575
11	HB-C	30 [± 40]	SHCal04	1810-1830 [9.4%] 1890-1920 [18.1%] 1950-1960 [40.7%]	1690-1730 [4.8%] 1800-1940 [45.8%] 1950-1960 [44.8%]	-	-

Table 2.

Calibrated age values of the samples (with the Calib Rev 5.0 program)

No. sample	Code sample	^{14}C age [error] (^{14}C yr BP)	Calibration dataset	CalAD age (cal yr AD)		Mean calBP age [error] (cal yr BP)	Age of sample (cal yr in 2005)
				1-σ range(s) [relative area]	2-σ range(s) [relative area]		
1	LT-C	1255 [± 35]	IntCal04	**685-778 [0.993768]** 795-795 [0.006232]	672-831 [0.915814] 836-869 [0.084186]	1220 [± 45]	1275
2	WB-1	360 [± 30]	IntCal04	**1466-1522 [0.577000]** 1574-1584 [0.072852] 1590-1625 [0.350149]	1451-1529 [0.500405] 1543-1634 [0.499595]	455 [± 30]	510
3	WB-3	370 [± 20]	IntCal04	**1463-1513 [0.738596]** 1601-1616 [0.261404]	1450-1523 [0.654462] 1560-1560 [0.001756] 1572-1629 [0.343783]	460 [± 25]	515
4	WB-4	1045 [± 20]	IntCal04	**990-1016 [1]**	907-911 [0.011011] 972-1024 [0.988989]	945 [± 15]	1000
5	LAS+1	555 [± 25]	IntCal04	1326-1343 [0.386673] **1394-1416 [0.613327]**	1315-1356 [0.443971] 1388-1427 [0.556029]	545 [± 10]	600
6	LAS	440 [± 25]	IntCal04	**1434-1454 [1]**	1423-1478 [1]	505 [± 10]	560
7	TT-000	865 [± 20]	IntCal04	**1167-1209 [1]**	1054-1077 [0.049361] 1154-1221 [0.950639]	760 [± 20]	815
8	TT-100	1090 [± 55]	IntCal04	**894-995 [0.960972]** 1007-1011 [0.039028]	781-790 [0.012603] 807-1028 [0.987397]	1005 [± 50]	1060
9	TT-220	530 [± 45]	IntCal04	1327-1342 [0.207827] **1395-1436 [0.792173]**	1307-1362 [0.339705] 1385-1446 [0.660295]	535 [± 20]	590
10	TT-270	480 [± 20]	IntCal04	**1425-1440 [1]**	1416-1445 [1]	520 [± 15]	575
11	HB-C	30 [± 40]	SHCal04	1817-1827 [0.177142] 1894-1916 [0.360601] 1951-1956 [0.462257]	1700-1723 [0.063439] 1809-1838 [0.201629] 1844-1867 [0.049400] 1878-1932 [0.360611] 1939-1942 [0.006257] 1950-1956 [0.318655]	-	-

RESULTS

Calibrated ages. The calibration of radiocarbon dates/ages (^{14}C ages) to calendar ages are listed in Table 1 (as calibrated with the OxCal v3.10 program) and Table 2 (as calibrated with the CALIB. 5.0 program). The 1-σ (68.2%) and 2-σ (95.4%) probability distributions, which define calAD age ranges of the dated samples, were obtained (calAD ages are rounded to the nearest 5 yr by the OxCal program and to the nearest year by the CALIB program).

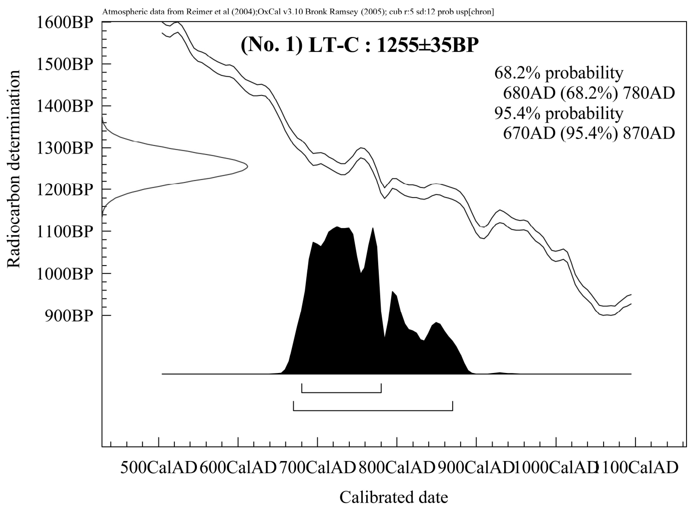

Fig. 1. The plotted OxCal calibration for sample No. 1.

From these values, we chose as the calAD age of each sample the corresponding 1-σ range (when only one range exists) or the corresponding 1-σ range with the highest probability (when there is more than one range). The selected calAD range of each sample is marked in bold.

Tables 1 and 2 also include the mean calBP age values and the corresponding errors of the samples (each rounded to the nearest 5 yr), calculated form the selected calAD range.

Shown are also calendar ages of the samples at the death of the tree. They were calculated from the corresponding mean calBP ages extrapolated (from AD 1950) to AD 2005. AD 2005 was chosen as the reference year for calculating sample ages, as the stems of Grootboom, where the samples originated from, collapsed between September 2004 and New Year 2005. Also rounding reasons pleaded for this year. In the case of sample No. 11, no calAD age interval was selected, for reasons to be explained later in this paper.

Results obtained with the two different programs, using both the same calibration datasets, are very similar. The 3 samples with high radiocarbon date were found to be millenarian, with ages of 1275 (No. 1), 1000 (No. 4) and 1050–1060 (No. 8) cal yr.

The plotted OxCal calibration results for the 3 millenarian samples are presented in Figs. 1–3.

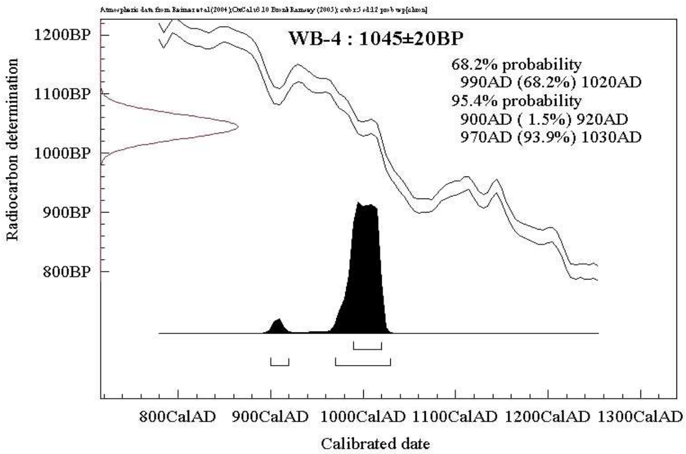

Fig. 2. The plotted OxCal calibration for sample No. 4.

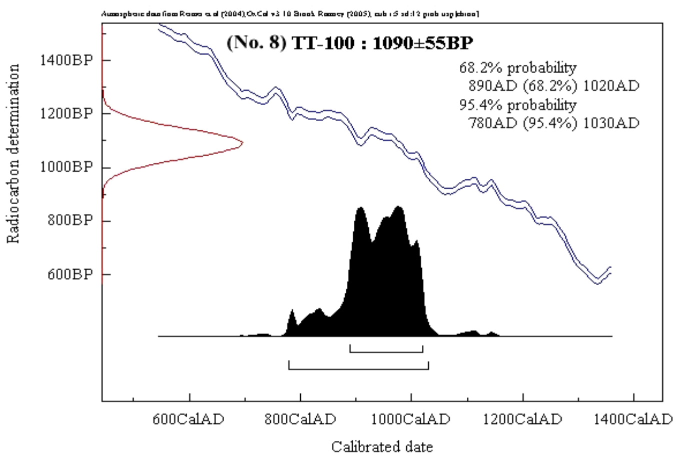

Fig. 3. The plotted OxCal calibration for sample No. 8.

DISCUSSION

Northern vs. Southern Hemisphere calibration. The radiocarbon calibration dataset is the result of committed work and significant joint efforts of numerous researchers over several decades. It is based on dating results of samples with known age collected almost exclusively form the Northern Hemisphere, especially dendro-dated wood and marine records.

Several studies have revealed, however, regional radiocarbon offsets. The most important is the so-called interhemispheric offset. Certain comparative studies evinced that trees from the Southern Hemisphere dated older than identically aged trees from the Northern Hemisphere. Such results suggest hemispheric differences in the distribution of ^{14}C throughout the troposphere. These differences are attributed to the larger expanse of ocean in the Southern Hemisphere and the atmosphere–ocean exchange [12-17].

The very first Southern Hemisphere calibration dataset was developed in 2002, based on several research on dated wood samples from New Zealand, Tasmania, Chile and South Africa, covering the period AD 1955–955. The SHCal02 calibration [18] is based on the IntCal 98 dataset for the Northern Hemisphere [19], corrected with a number of results from the Southern Hemisphere. The SHCal02 dataset indicates older ^{14}C ages by ca. 8–80 yr in the Southern Hemisphere, with a mean offset of 41 ± 14 yr for the period cal AD 1850–950 and also shows a periodicity in the offset of about 130 yr.

The International Radiocarbon Conference in Wellington, New Zealand recommended the use of the SHCal02 dataset for samples with cal AD 1850–950 (0–1000 cal yr BP) ages from the Southern Hemisphere [11]. The Southern Hemisphere is defined as south of the thermal equator or south of the Intertropical Convergence Zone (ITCZ). The ITCZ is the region that circles the Earth and extends from about 5º N to 5º S, where the northeast and southeast trade winds converge in a low pressure zone.

There are, however, seasonal shifts in the ITCZ that may bring atmospheric CO_2 from the Northern Hemisphere to a site for part of the year and from the Southern Hemisphere for another part. This seasonal migration of the ITCZ, combined with multi-decadal and millennial migrations in the past, poses some uncertainties for calibration of dated samples from tropical and neo-tropical sites [11].

The SHCal02 dataset, corrected and completed with new research data, determined in 2004 the development of the SHCal04 calibration dataset, which covers a much longer period, between 0–11 cal kyr BP [11]. The SHCal04 Southern Hemisphere calibration is associated with the new developed IntCal04 Northern Hemisphere calibration for the period 0-26 cal kyr BP [10] (Fig. 4). SHCal04 shows a larger interhemispheric offset than the previous SHCal02 that varies only slightly from 55 to 58 yr.

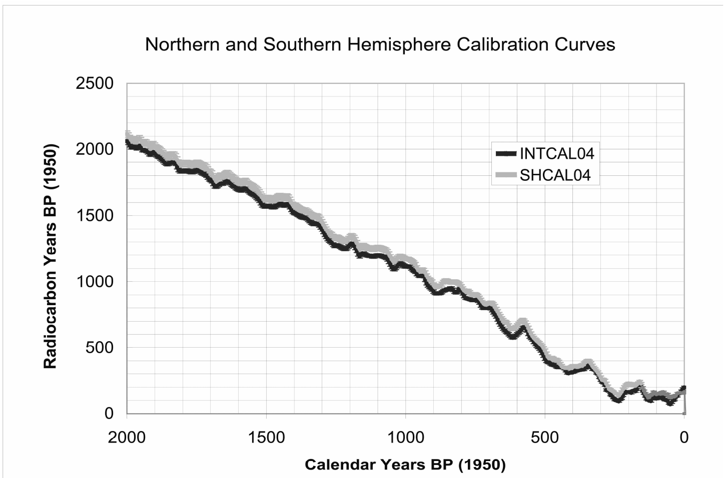

Fig. 4. Plotted IntCal04 and SHCal04 calibration datasets for the period 0–2000 cal yr BP. The difference (for a certain calendar year BP value) between the SHCal04 and IntCal04 curves (expressed in radiocarbon years BP) corresponds to the offset.

Nevertheless, the calibration of the dated samples collected from Grootboom was performed by using the atmospheric data from Reimer et al., i. e. the very large and well documented IntCal04 terrestrial calibration dataset [10]. The reasons for this choice are the following:

i) The SHCal Southern Hemisphere calibration is based on a relatively scarce number of dating results of wood samples from mid-latitude areas, which suggest a mean interhemispheric offset of several decades. On the other hand, alternative studies show no or very small interhemispheric offset values [20-22]. A very recent extended research done on Tasmania huon pine (*Lagarostrobus franklinii*) decadal samples do not document a distinguishable offset from the Northern Hemisphere for the time period 1550–2100 cal yr BP [23].

ii) The Grootboom site is located at relatively small latitude, ca. 19º S, right in the intertropical area, for which there are some uncertainties concerning calibration. We outline that all results used for the Southern Hemisphere calibration originates from wood samples collected from greater latitudes. It should be also noticed that some research suggests intrahemispheric offsets between samples collected form different latitudes of the same hemisphere [24-28, 14-15].

Only the youngest sample (No. 11), with a ^{14}C age of 30 ± 40 yr BP, was calibrated using the atmospheric data from McCormac et al., i. e. the SHCal04 calibration dataset [11], because this recent period is much better documented and a small interhemispheric offset was demonstrated.

One should notice that the calibration of the samples using the SHCal04 dataset leads to lower calendar age values, with an offset of several decades.

Age of samples. Trees take up atmospheric CO_2 by photosynthesis. CO_2 is being used in part for the quasi-continuous building of the wood texture of the trunk and branches. As other trees, the African baobab grows due to cambial activity which, during the rainy season, adds every year new layers of woody tissue. Dead wood does no longer exchange CO_2 with the environment.

Beside structural non-mobile carbon components, mainly cellulose, which have been synthesized at the very moment of the original formation of the respective woody tissue, the wood (xylem) also contains non-structural mobile carbon components, which are formed earlier or later and are removed by pretreatment of samples

While the stable isotope (i.e. ^{12}C and ^{13}C) content of the wood remains constant over time, the amount of the unstable ^{14}C isotope, also called radiocarbon, gradually decreases via radioactive beta minus decay. Thus, ^{14}C emits continuously electrons and is converted to nitrogen, according to reaction:

$$^{14}C \rightarrow {}^{14}N + e^{-} \ .$$

By determining the ^{14}C content, relative to the content of stable carbon, of a pretreated wood sample, one can date that particular sample.

The age of a certain position in the trunk or branches is calculated starting with the moment of the original formation of the respective woody tissue. Theoretically, the true age of a certain position is equal to the age of a pretreated wood sample collected from the respective location, which was dated and calibrated.

However, in certain cases, especially of tree species with soft and spongy wood, the age of one particular sample may differ, more or less, from the true age of the corresponding position.

The age of several samples collected from the remains of Grootboom belong to this category, such as the dating results suggest. One can distinguish the following three cases:

i) Samples collected from the rim of hollow parts. Beside hollows generated by elephants or by fire, hollows are generally formed by twisting movements of large branches, due to their growth and/or excessive weight, which may rotate and break the soft wood of the baobab trunk. Thus, at the moment when a hollow forms, woody tissues are displaced from their original position. On the other hand, certain tree species, including the African baobab, show the tendency to partially repair over time the hollows with amounts of new wood, especially for hollows relatively close to the external surface of the trunk. In special cases, such as the Livingstone baobab of Chiramba (Mozambique) or Holboom, another huge Namibian baobab located at only 8 km from the Grootboom site, it was reported that rims of an internal hollow can be covered over time with new bark.

ii) Samples collected in the vicinity of contact or fusion areas between neighboring stems. For trees with multiple stems, the neighboring stems may eventually get in contact and may even fuse together. Production of woody tissue can continue in contact and in fusion areas, even when no free place would be available for growth. Thus, a wood sample collected from such a location may contain woody tissues of different ages, which are mixed together.

ii) Samples collected from collapsed stems. In the case of tree species with soft and spongy wood, the collapsed stems are damaged and get bent due to their own weight. Thus, woody tissues from different positions may mix together. Samples collected along the central axis, parallel to the ground, may also contain younger wood, which originates from positions located towards the upper part of the fallen stem.

Consequently, samples collected from the rim of hollows, in the vicinity of contact or fusion areas between stems or from collapsed and damaged stems may date younger than the true age of the position from where they are collected. On the other hand, such samples may even be non-homogenous, containing woody tissues of different ages in variable proportions.

In the light of these remarks, the only samples whose dated and calibrated age is identical or very close to the true age of their corresponding position in the trunk are those which were collected from a remaining stump of a fallen stem, from a location away from the rim of a hollow and also not very close to a contact or fusion area between two neighboring stems. These conditions are met only by one of the samples collected from Grootboom, namely No. 3.

Discussed below are calibrated ages of the dated samples (Tables 1 and 2). The samples collected from four different stems are numbered (from No. 1 to No. 10) from west to east, facing north, considering their original position in the trunk prior to collapse [1].

Sample No. 1, ca. 1275 yr. This is the oldest sample of the tree, collected at a height of ca. 1.20 m and at a distance of ca. 0.40 m from the center of the remaining stump of stem A, the last to collapse around New Year's eve 2005.

Sample No. 2, ca. 510 yr. The sample originates from the stump of stem B and it was collected at a height of ca. 1.90 m and a distance of only ca. 0.20 m from the contact and partial fusion line between stems A and B. Its age is suspected to be younger than the true age of the corresponding position. In addition, the wood of the sample is much more compact and dense relative to other samples, suggesting that a large number of woody tissues had been added to this location and had been pressed together over time.

Sample No. 3, ca. 515–520 yr. This is an extreme lateral sample, collected at a height of ca. 2.30 m and at only 0.10 m from the southern edge of the remaining stump of stem B.

Sample No. 4, ca. 1000 yr. It is another millenarian sample, collected from the stump of stem B, at a height of ca. 1.40 m and also from the rim of the largest internal hollow of Grootboom. The corresponding position was shifted towards the southern flank.

Sample No. 5, ca. 600 yr. This sample was collected from the collapsed stem C. In the standing stem, the corresponding position was located close to the rim of a large hollow, at a height of ca. 2.60 m above ground level.

Sample No. 6, ca. 560 yr. It was collected, like sample No. 5, from the fallen stem C, from a position located at the rim of the same very large hollow and a height of ca. 2.40 m above ground level.

Sample No. 7, ca. 815–820 yr. This sample was collected from the rim of a small hollow, located just in the core/center of the fallen stem D, the largest of the tree. It had a rather sandy aspect, being severely decayed due to microorganisms which destroyed the fibrous structure of the wood. Its age is suspected to be considerably younger than the true age of the corresponding position. All samples originating from stem D were located near ground level in the standing trunk.

Sample No. 8, ca. 1050–1060 yr. It is the second oldest sample of the tree, which was collected from the rim of a hollow of the collapsed stem D, from a position located initially at 1.00 m towards east, relative to sample No. 7.

Sample No. 9, ca. 590 yr. The sample was collected from the fallen stem D, from a position situated at 1.20 m towards east, as compared to sample No. 8.

Sample No. 10, ca. 575 yr. This is another extreme lateral sample, collected from the fallen large stem D. Prior to collapse, it was located at only 0.25 m from the eastern extremity of the stem and of the whole trunk.

Sample No. 11, no selected age. This sample was collected at 1.60 m from the top of the unbroken fallen high branch, with a measured length of 26.31 m, following its contour.

The calibration and interpretation of radiocarbon dating for samples formed after AD 1640 is problematic and is characterized by low accuracy. This is mainly due to industrial fossil fuel burning, which involved large emissions of million-year old practically ^{14}C-free carbon in atmosphere. The high variations of ^{14}C concentration in the atmosphere over the industrial period, known as the Suess effect, affected to a larger extent the Northern Hemisphere, which was more advanced [29]. The incorporation in living tissues, including those which became shortly thereafter dead wood, of CO_2 from the period of the Suess effect produces generally an overestimation of the ^{14}C age of the corresponding samples. This determines that a calibration of a sample from this period results in up to five cal age ranges for one ^{14}C age [30].

The ^{14}C age of sample No. 11, i. e. 30 ± 40 yr BP, corresponds to three 1-σ ranges (calibrated with OxCal and CALIB), respectively to three 2-σ ranges (calibrated with OxCal) and even to six 2-σ ranges (calibrated with CALIB) (Tables 2-3). The 1-σ range and also the 2-σ range with the highest probability correspond, with both calibration programs, to the period AD 1950–1960 (rounded values).

The 1950–1960 decade is also known for the beginning of the dramatic period of troposphere bomb tests. Due to the 404 atmospheric nuclear detonations between 1953–1963, a large amount of artificial ^{14}C was injected into the stratosphere. Consequently, the ^{14}C concentration in the troposphere almost doubled from 1950 to 1964 [31-33]. Again, the Northern Hemisphere, where the large majority of nuclear weapon tests took place, was affected earlier and to a more significant extent than the Southern Hemisphere. Incorporation in living tissues of CO_2 from the bomb tests period, which contains modern carbon very rich in ^{14}C, determines generally an underestimation of the ^{14}C age of the respective sample. The calibration of a sample from this period also results in three or more cal age ranges for one ^{14}C age.

Given that both the Suess effect and the bomb tests affected to different extents the two hemispheres, these differences being relatively well documented, determined us to use the SHCal04 dataset to calibrate the ^{14}C age of sample No. 11.

Selection of a reliable/accurate cal age range is, however, almost impossible. The range AD 1950–1960, which has the highest probability, is practically excluded, even if the ^{14}C age is probably underestimated. This is due to a large number of testimonies that state that Grootboom practically had not changed at all from its discovery in ca. 1890 until its sudden death. What is certain is that sample No. 11 was formed after AD 1640, thus having an age of less than 365 cal yr. In our opinion, the age of sample No. 11 is probably between 200–300 yr.

Structure of Grootboom. The enormous trunk of Grootboom collapsed very chaotically in all directions, so that six fallen stems have been eventually identified. After the fall of the last stem to the ground, the remains of Grootboom looked as if the tree would had been bombed or blasted with dynamite.

The six stems were marked (from west to east and than to northeast, facing north) by: A, B, C, D, E and F, in the reverse order of collapse [1].

The dated samples were collected from four stems, namely A, B, C and D. The fluctuation of the age of samples and the presence of 3 millenarian samples in three different stems strongly indicate that the trunk of Grootboom was made up of several (the more or the less) fused stems.

Considering the dating results and other information, we will try to answer the following question: How many and which of the six fallen stems had been independent, i. e. belonged to the original structure of Grootboom?

Discussed and analyzed below are the six stems, which were all of oval shape. The estimated values of the largest dbh (diameter at breast height) and of the dbh in perpendicular direction are presented in brackets.

Stem A (ca. 2.5 m x 1.2 m). This stem, which collapsed the last, was located at the western extremity of the trunk (facing north). It was located next to trunk B towards east, the two stems being partially fused up to a height of ca. 1 m above ground level. Its small dimensions are somewhat surprisingly, especially because it had enough free room to grow towards west. The oldest dated sample (No. 1) was collected exactly from stem A.

Stem B (ca. 3.1 m x 1.8 m). Stem B was located in between stems A and C and had no free room for additional growth. The third oldest sample (No. 4) was collected form this stem, more precisely from the rim of the largest hollow of the tree.

Stem C (ca. 1.6 m x 0.8 m). This small stem was fused up to a height of ca. 2 m with other three stems: B (towards west), D (towards east) and E (towards northeast). Its reduced dimensions and the relatively young age of the samples collected from it (Nos. 5 and 6) reveal that stem C must have been only a fusion product of the three stems, that continued to produce woody tissue after fusion.

Stem D (ca. 5.5 m x 3.2 m). Stem D, obviously the largest of the tree, was located at the eastern extremity of the trunk. It was the only stem which fell with roots exposed. Stem D was partially fused with stems C (towards west) and E (towards north). After breakdown, its base diameter parallel to the ground was measured and found to be 5.90 m. The second oldest sample (No. 8) was collected from this stem.

Stem E (ca. 3.0 m x 2.0 m). Stem E, which originates form the eastern flank of the trunk, was fused with stem D (towards south) and was in contact with stem F (towards north). It was unavailable for sampling, as it was partially hollow and also almost entirely covered and crushed by other fallen stems.

Stem F (ca. 3.5 m x 3.2 m). This stem, the first which collapsed, was almost isolated at the northeastern extremity of the trunk. It had only a connection area near ground level with stem E. The partially hollow stem F had already been severely decayed at the moment of the first sampling and no sample was collected from it.

These data suggests that five stems (A, B, D, E and F) may be considered independent and they are likely to belong to the original structure of Grootboom. The sixth stem (C) was much younger, being the result of fusion of three vicinal independent stems.

As already mentioned, there are two possibilities for the genesis of a baobab with multiple stems [34]. The first possibility is multiple sprouting from the same rootstock of a fallen parent tree. Hence, the stems are clones of the parent tree and they look very similar, because they are genetically identical. The second possibility is the simultaneous germination of several seeds. In this case, the stems are genetically different and they look somewhat different, for instance they may break into leaf at a different time and the tint of leaves and bark may also be somewhat different.

No such differences have been observed for Grootboom. This fact supports the hypothesis that the five independent stems sprouted simultaneously and fused into a single trunk at some later time. Consequently, one can state that morphologically Grotboom was a quintuple tree, while genetically it was a single individual.

The moment of complete fusion can be estimated by means of the age of samples collected from the fusion stem C (Nos. 5 and 6) and near the fusion area in between stems A and B (No. 2). Considering some corrections, we estimate that the five independent stems fused into a single trunk ca. 600–800 yr ago.

It should be also noticed that other very large African baobabs obviously have or are suspected of having multiple stems. We mention here the following trees: Chapman baobab at Gootsa pan (in Botswana), Dorslandboom in Bushmanland (in Namibia), Platland baobab near Duiwelskloof (in South Africa), Big tree at Victoria Falls and Big baobab at Devuli/Mokore ranch (in Zimbabwe), Big baobab near Joal (in Senegal).

Age of Grootboom. The 3 oldest dated samples with ages of at least 1000 yr, collected from three different stems, evince beyond doubts that Grootboom was a millenarian tree. Grootboom's true age can be estimated from the age of the oldest sample and its position in the respective stem. Sample No. 1, with a calendar age of 1,275 ± 50 yr, was collected from the stump of the relatively small stem A, located at the western extremity of the trunk, at a height of 1.20 m above ground and a distance of 0.40 m from the calculated position of its core which was hollow. These results reveal that the age of Grootboom was of +1,275 yr, i.e. the tree was older than 1,275 yr (our estimate is 1,350–1,500 yr).

Growth rate. The classic concept of growth rate of the whole trunk is meaningless for trees with multiple stems. One can only evaluate growth rates of independent stems and their dynamics, taking into account that the growth of each stem is limited by other stems in at least one direction.

In the particular case of Grootboom, one should notice that all stems had a clearly oval shape. Thus, the west-east diameter of the first three independent stems (A, B and D), from which samples were collected, was almost twice larger than their north-south diameter. This appears to be surprising as these stems had much more available room for growing towards north and south than towards west and east. Consequently, the growth rate in the west-eastern direction was almost twice greater than the growth rate in north-southern direction. For the other two stems (E and F), the west-east growth rate was also greater.

Because in case of multiple sprouting all independent stems are of the same age, i. e. +1275 yr, for each stem one can calculate the mean growth rate in two perpendicular directions. Mean growth rate values at breast height (grbh) for the entire life cycle of Grootboom are shown in Table 3. Given that in these calculations, we used the minimum age value (1275 yr), the growth rate data presented can be considered as representing the upper range values. The presented values for the mean growth rate (expressed in 10^{-3} m·yr^{-1}) correspond to the mean annual increase in radius (expressed in 10^{-3} m or mm).

Table 3.

Mean growth rate values of the independent stems

Stem	Age (cal yr)	Diameter at breast height (m)		Mean growth rate at breast height/ /annual increase in radius (10^{-3} m·yr^{-1})	
		dbh 1 [WE]	dbh 2 [NS]	grbh 1 [WE]	grbh 2 [NS]
A	+1275	2.50	1.20	0.98	0.47
B	+1275	3.10	1.80	1.22	0.71
D	+1275	5.50	3.20	2.16	1.25
E	+1275	3.00	2.00	1.18	0.78
F	+1275	3.50	3.20	1.37	1.25

The largest mean growth rate is the west-east value for stem D (2.16 x 10^{-3} m·yr^{-1}), while the smallest is the north-south value for stem A (0.47 x 10^{-3} m·yr^{-1}).

These mean values do not reflect, however, the growth dynamics of Grootboom's stems. According to published accounts, the growth rate of the African baobab decreases severely with the age [35, 36, 37, 38]. This statement can be also verified in the case of

Grootboom, by the ratio of the position of the extreme lateral samples to their age.Ages of extreme lateral samples (Nos. 3 and 10) show that over the past ~520 yr stem B grew by only 0.10 m towards south, while stem D grew by 0.25 m towards east in ~575 yr, even though there was enough room in both directions (no neighbouring stem). The calculated growth rate values are very small: 0.19 and 0.43×10^{-3} m yr^{-1} (corresponding to a mean annual increase in radius by only 0.19 and 0.43 mm). Such values reveal that over the past 500–600 yr Grootbooom almost ceased growing.

When compared to historic records of the same trees, measurements of several huge individuals from Botswana and Mozambique showed a very small increase or even a decrease in girth during a time span of ~110 yr, from 1850–60 to 1966 [39]. These results were attributed to an obvious decrease of rainfall in Central Southern Africa. Our dating results of Grootboom suggest that the period of prolonged drought may have begun several centuries earlier, probably around AD 1400–1500.

Age limit of the African baobab. Preliminary dating results of the samples collected from Grootboom strongly support the long lived baobab hypothesis or at least that certain individuals of the species may become millenarians. The oldest sample indicates an age of +1275 yr for Grootboom, while our estimates augment the age up to 1350–1500 yr. One should consider that shortly before its demise Grootboom looked healthy and seemed not to be a very old and decrepit tree, nearing its end. It is very likely that it was attacked and killed by the poorly studied baobab disease. Had this unfortunate event not happened, Grootboom might have probably lived for additional years. Therefore, we estimate that the age limit of the African baobab, which is probably identical to the age limit of angiosperms, is around 1,500 yr.

History of Grootboom. The acquired data suggests the following scenario for the history of Grootboom. Over 1275 yr ago (prior to AD 730), maybe 1350–1500 yr ago (around AD 500–650), a very large African baobab collapsed somewhere in Central Southern Africa, in a semi-arid area habited only by San people or Bushmen. Five sprouts/shoots developed from the prostrate parent, which could be named Ur-Grootboom.

The five young baobabs, which were clones of the parent tree, grew gradually, until 600–800 yr ago (around AD 1200–1400), when they fused together into a single huge trunk, which came to be known much later as the Grootboom baobab. About 500–600 yr ago (around AD 1400–1500), the trunk of Grootboom was almost as large as at the time of its death. Presumably, climate changes in the area, especially shift towards conditions of prolonged drought, almost stopped its growth.

In AD 1890, Grootboom was discovered by the modern world, namely by the Dorslandtrekkers, a group of Boers who withdrew from South Africa to Angola. The tree, which looked very healthy, had not changed its physical appearance until AD 2004, when it unexpectedly died, being probably killed by the still mysterious baobab disease. Grootboom begun to collapse stepwise, until the last stem fell around New Year AD 2005. At the beginning of AD 2006, the last traces of Grootboom disappeared completely, leaving behind only the memories of what once was a mighty baobab tree.

CONCLUSIONS

Grootboom, the world's largest African baobab tree, dies and collapsed unexpectedly in Bushmanland, Namibia, in late 2004. Six fallen stems have been identified on the ground.

The international research project started on this occasion had the following aims: 1) to determine accurately the true age of the tree; 2) to establish whether Grootboom's trunk was a single unit or was composed of several fused stems; 3) to learn about the dynamics of Grootboom's growth rate during its life cycle.

11 samples collected from the remains of the collapsed tree were processed and analyzed by AMS radiocarbon dating. Several additional samples are under investigation.

The presented results and conclusions of the research can be summed up as follows:

1) The radiocarbon age (^{14}C age) values of 3 samples (Nos. 1, 4 and 8), collected from three different stems, was greater than 1000 yr BP, i. e. 1255, 1045 and 1090 yr BP. These are the first samples of an angiosperm tree, with accurate dating results, older than 1000 yr.

The radiocarbon age of the oldest sample (No. 1) was found to be 1255 ± 35 yr BP, which corresponds to a 1-σ calendar age of 1275 yr, at the moment of the tree's demise.

Grootboom becomes the first millenarian angiosperm tree, with an age of +1275 yr. Our estimate of the age is around 1350–1500 yr, according to the position of the oldest sample in the corresponding stem prior to collapse.

2) The acquired results indicate that five stems may be considered independent, belonging to the original structure of Grootboom, while the sixth stem was the result of fusion of three vicinal independent stems.

The five (genetically identical) independent stems sprouted simultaneously from a parent tree and they fused into a single trunk at some later time. The age of samples collected from the fusion stem (Nos. 5 and 6) and near the fusion area of two neighboring stems (No. 2) suggest that the five stems fused into a single trunk around 600–800 yr ago.

One can state that morphologically Grootboom was a multiple tree, but genetically it was a single individual.

3) The age of the extreme lateral samples (Nos. 3 and 10) reveals that Grootboom grew by only ca. 0.10 m towards the southern edge and 0.25 m towards the eastern extremity over the past ca. 500–600 yr. The severe decrease of the growth rate could be ascribed to climate changes in Central Southern Africa, i.e. a shift towards conditions of prolonged drought.

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