STUDIA UBB CHEMIA, LX, 4, 2015 (p. 7-20)
(RECOMMENDED CITATION)

RADIOCARBON DATING OF AFRICAN BAOBABS WITH TWO FALSE CAVITIES: THE INVESTIGATION OF LUNA TREE

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ABSTRACT. The paper discloses the radiocarbon investigation results of the Luna tree, a representative African baobab from Venetia Limpopo Nature Reserve, South Africa. Several wood samples collected from deep incisions in the trunk were investigated by AMS (accelerator mass spectrometry) radiocarbon dating. The age sequence of segments extracted from the oldest sample demonstrates that ages increase with the distance into the wood up to a point of maximum age, after which ages decrease toward the sample end. This anomaly is typical for multi-stemmed baobabs, having a closed ring-shaped structure with a false cavity inside. Dating results reveal that each of the two large fused units, which build the Luna tree, consist of such a closed ring. The two closed rings include two interconnected false inner cavities. False cavities are empty spaces between fused stems that were never filled with wood. We named this baobab architecture, which has a very high symmetry, double closed ring-shaped structure with two false cavities. The new architecture, which is very uncommon, enables baobabs to reach large sizes and very old ages. The radiocarbon date of the oldest sample segment was 1507 ± 22 BP, which corresponds to a calibrated age of 1405 ± 20 yr. We estimate that the oldest part of Luna tree has an age of 1600 ± 100 yr. By these results, the Luna tree becomes the fourth oldest African baobab with accurate dating results.

Keywords: *AMS radiocarbon dating, Adansonia digitata, tropical trees, age determination, inner cavity, multiple stems.*

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INTRODUCTION

The genus *Adansonia* which belongs to the Bombacoideae, a subfamily of Malvaceae, consists of nine species. The African baobab (*Adansonia digitata* L.), which is the biggest and best-known of the *Adansonia* species, has a natural distribution in mainland Africa between the latitudes 16º N and 26º S, especially in savanna regions. It can also be found outside Africa, in areas throughout the tropics, where it was introduced [1-7].

Large baobabs are considered living natural monuments. Based on the impressive size of several specimens, certain tree experts considered that the baobab lives to an old age, possibly over 1,000 years. The age of the oldest baobab specimens has remained, however, a controversial topic. Dating accurately large baobabs has proven to be a very difficult task, due to their wide trunk, the presence of hollow parts and the rather faint growth rings [1,4-13].

The baobab produces faint growth rings, considered by many researchers to be annual rings. Nevertheless, for large and old baobabs, a hypothetically accurate ring counting is not possible, as growth rings may no longer be observed in certain areas of the trunk and they are also missing in the area of large cavities [1,5,6]. In addition, for several large baobab stems we identified the growth stop phenomenon, which is due to old age or to prolonged stress conditions. We also found that for several baobab architectures, when considering a given wood segment, the number of counted rings is typically lower than the calendar age determined by radiocarbon dating; this difference increases with the age of the segment. That is why ring counting and ring width analysis are not effective for evaluating the age of big baobabs. Therefore, radiocarbon dating represents the sole accurate method for determining the age of large and old baobabs [5,12-20].

In 2005, we started an in-depth research project to elucidate several controversial or poorly understood aspects regarding the architecture, growth and age of the African baobab. This research is based on our new approach which enables investigation of standing live specimens. Our approach consists of AMS (accelerator mass spectrometry) radiocarbon dating of small wood samples collected especially from inner cavities, but also from deep incisions/ entrances in the stems, fractured/broken stems and from the outer part/exterior of large baobabs [16,20]. This methodology involves a very careful analysis and interpretation of the AMS radiocarbon dating results.

The dating results have revealed that all large baobabs are typically multi-stemmed. The radiocarbon investigation of large African baobabs has demonstrated that their architecture is much more complex than previously believed. We identified the so-called open and closed ring-shaped structures, which are the most important architectures that enable African baobabs to reach old ages and large sizes. We also described the false cavities, which are large natural empty spaces between fused stems disposed in a closed ring-shaped structure. The oldest dated *A. digitata* specimens were found to have ages up to 2000 years. According to these values, the African baobab becomes the angiosperm with the longest life span [5,12,13,15-17,20].

Here we describe a new variation of the closed ring-shaped structure, namely baobabs with two fused closed rings and two false cavities. We identified this new architecture in the investigation of Luna tree, a large and old baobab from South Africa.

RESULTS AND DISCUSSION

The Luna tree and its area. The Luna tree is located within the Venetia Limpopo Nature Reserve, Limpopo Province, South Africa. The Venetia Reserve is positioned in the most northern part of South Africa, slightly south of the meeting point with Botswana and Zimbabwe. It is a private fenced park, with an extent of 345 km^2, owned by De Beers Diamond Mining Company. The Luna tree is situated in the former Luna farm, close to the Venetia Diamond Mine, the largest producer of diamonds in South Africa. Its GPS coordinates are 22º22.830' S, 029º22.065' E and the altitude is 682 m. Mean annual rainfall in the area is 366 mm (Pontdrift station).

Figure 1. General view of Luna tree taken from the west, during the dry season.

Figure 2. General view of Luna tree taken from the east, during the wet season. The sampling point 4 is also shown.

The Luna tree has a maximum height of 17.2 m, the circumference at breast height (cbh; at 1.30 m above ground level) is 20.02 m and the overall wood volume (trunk and branches) is around 170 m^3. The big trunk consists of two large units (A and B), which are almost completely fused up to a height of ca. 3-4 m and has a prominent buttressed base (**Figures 1 and 2**).

The two units have distinct canopies. On the western side, over the buttress, there are two deep scars in both units, which originate from severe damages in the past, probably including fire episodes. The scar in the northern unit (A) is considerably larger than that in the southern unit (B). Between the two scars, at a height of 1.48 m above ground, there is a narrow elliptical opening into a large central cavity (**Figure 3**). The opening is accessible only for bats and small animals; it is, however, large enough for taking photographs and laser measurements inside. The cavity consists of two connected rooms. The quasi-conical northern cavity room (in unit A) has an ellipsoidal basis, with the axes of 1.98 x 1.35 m and a height of 5.32 m to the ceiling; the corresponding dimensions of the southern cavity room (in unit B) are of 2.41 x 1.70 x 6.69 m. The inner cavity walls are completely covered by bark.

Wood samples. Four wood samples were collected from the outer part of the two units which build the trunk of Luna tree. Two samples (labelled 1 and 2) originate from the large scar in unit A (located on the western side), while one sample (labelled 3) was extracted from the scar in unit B (also, on the western side) and another (labelled 4) from an incision on the opposite part (eastern side).

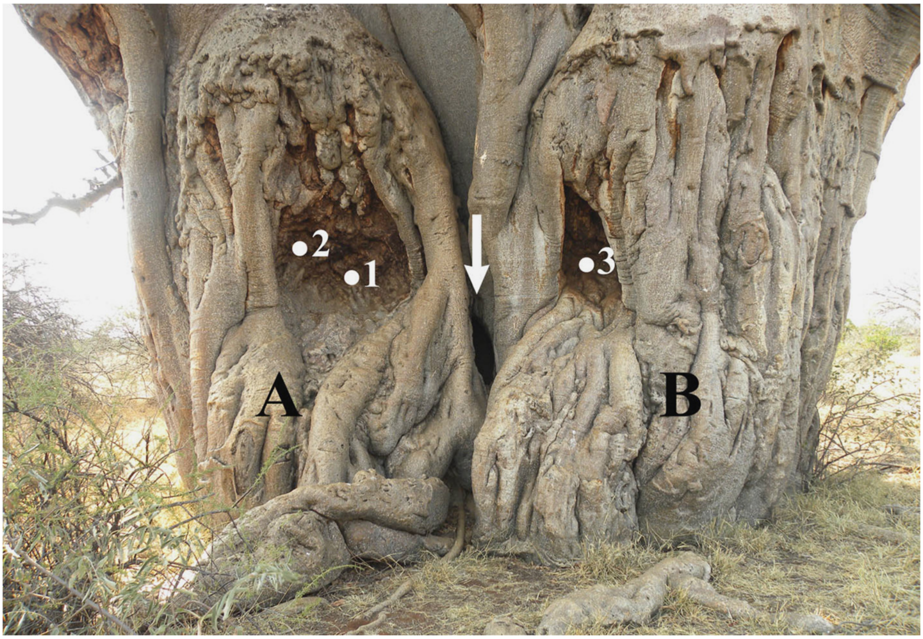

Figure 3. Detail of the western side of Luna tree showing the two units of its trunk (A, B), the two large scars, three sampling points (1, 2, 3) and the opening into the cavity (marked by an arrow).

Given the buttressed trunk, the samples were collected at greater heights than usually, i.e., 2.35, 2.60, 2.40 and 2.60 m. Even if the penetration of the borer in the wood was quasi-complete in all cases, the four samples are relatively short, namely 0.175, 0.22, 0.22 and 0.265 m; this reveals the presence of hollow parts inside the two units. The sampling positions are shown in **Figures 2, 3 and 4**. Thirteen small pieces/segments, each of the length of 0.001 m (marked as a, b, c, d), were extracted from determined positions of the four samples. The segments were processed and investigated by AMS radiocarbon dating.

AMS results and calibrated ages. Radiocarbon dates of the 13 segments extracted from the four samples are listed in Table 1. Radiocarbon dates and errors were rounded to the nearest year. The radiocarbon dates are expressed in ^{14}C yr BP (radiocarbon years before present, i.e., before the reference year AD 1950).

Calibrated (cal) ages, expressed in calendar years, are also shown in Table 1. The 1-σ probability distribution was selected to derive calibrated age ranges. For four sample segments, the 1-σ distribution is consistent with only one calibrated age range, while for other five segments the 1-σ distribution corresponds to two age ranges. For these segments, the confidence interval of one range is, with one exception, considerably greater than that of the others; therefore, it was selected as the cal AD range of the segment for the purpose of this discussion. For segment 4b, the two confidence intervals have close values, both being selected as cal AD ranges.

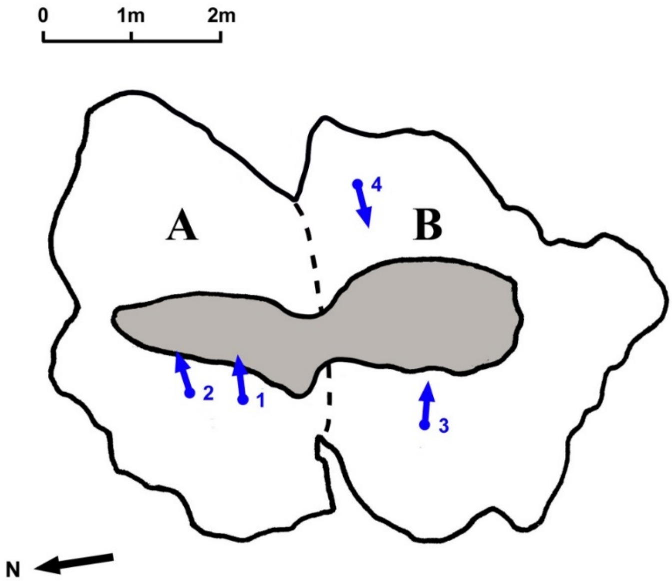

Figure 4. Transversal section of the trunk of Luna tree at 1.3 m above ground. The two units (A, B) and the projection of sampling points (1-4) are marked. The false cavity inside the two units is displayed in grey.

To obtain single age values of sample segments, we derived a mean calendar age of each segment from the selected range (marked in bold). Ages of segments represent the difference between AD 2015 and the mean value of the selected range, with the corresponding error. Ages and errors were rounded to the nearest 5 yr.

For four sample segments, ages fall after AD 1950 (0 BP), namely the ^{14}C activity, expressed by the ratio $^{14}C/^{12}C$, is greater than the standard activity in the reference year 1950. Such values, which correspond to negative radiocarbon dates, are termed greater than Modern (>Modern). In these cases, the dated wood is young, being formed after AD 1950.

Table 1. AMS Radiocarbon dating results and calibrated calendar ages of samples/segments collected from the Luna tree.

Sample (Segment)	Depth[1] [height[2]] (10^{-2} m)	Radiocarbon date [error] (^{14}C yr BP)	Cal AD range 1-σ [confidence interval]	Sample age [error] (yr)
1a	5.5 [235]	880 [± 24]	**1181-1226 [68.2%]**	810 [± 20]
1b	11.5 [235]	1507 [± 22]	**590-632 [68.2%]**	1405 [± 20]
1c	14.5 [235]	1280 [± 25]	**766-860 [68.2%]**	1200 [± 45]
1d	17.5 [235]	870 [± 25]	**1185-1230 [59.3%]** 1251-1260 [8.9%]	810 [± 20]
2a	5 [260]	–	–	>Modern
2b	17 [260]	75 [± 26]	1816-1832 [24.6%] **1892-1922 [43.6%]**	110 [± 15]
2c	21.5 [260]	–	–	>Modern
3a	5 [240]	909 [± 24]	**1162-1211 [68.2%]**	830 [± 25]
3b	15.5 [240]	–	–	>Modern
3c	21.5 [240]	–	–	>Modern
4a	7.5 [260]	64 [± 29]	1816-1832 [24.8%] **1892-1923 [43.4%]**	110 [± 15]
4b	18.5 [260]	709 [± 28]	**1292-1316 [33.2%]** **1356-1381 [35.0%]**	710 [± 10] or 645 [± 15]
4c	25.5 [260]	975 [± 30]	**1045-1094 [37.8%]** 1106-1153 [30.4%]	945 [± 25]

[1] Depth in the wood from the sampling point.
[2] Height above ground level.

Dating results of samples (segments). The most interesting dated sample is 1, out of which we investigated four segments. Two segments, 1b and 1c, were found to have radiocarbon dates considerably greater than 1000 BP. The oldest segment 1b originates from a distance of 0.12 m in the wood from the sampling point; the latter is located at a depth of ca. 0.85 m in the large incision/scar in unit I. Its radiocarbon date of 1507 ± 22 BP corresponds to a calibrated calendar age of 1405 ± 20 yr. The second oldest segment 1c, which originates from a depth of 0.15 m into the wood, was found to have a radiocarbon date of 1280 ± 25 BP and an age of 1200 ± 45 yr. The dating results of the four segments extracted from sample 1 show that the age values increase with the distance/depth into the wood up to a point of maximum age, i.e., segment 1b, after which they decrease toward the cavity.

The ages of two segments of sample 2, i.e., 2a and 2c, fall after AD 1950, being unexpectedly young. The age of the middle segment 2b is also young, around 110 yr. Such values demonstrate that the three dated segments consist of recent regrowth layers and not of the original old wood. Baobabs exhibit an unusual self-healing ability deep within the stem and also in their larger or smaller cavities. The new growth layers are due to repairing the interior xylem after significant wood damage, likely triggered by fire [16]. The ages of segments extracted from sample 2 evince at least two significant damages in this area of Luna tree, which occurred around AD 1900 and after AD 1950. The last fire damage after AD 1950, which triggered the youngest regrowth layer, affected not only the outer part, but also the cavity inside unit I.

For sample 3, only the first segment 3a consists of the original old wood. Its radiocarbon date of 909 ± 24 BP corresponds to a calibrated age of 830 ± 25 yr. The ages of the deeper segments 3b and 3c, which are very close to the cavity inside unit B, fall after AD 1950 and consist of regrowth. These results show that the last fire affected to a certain extent both rooms of the cavity.

For sample 4, the only one collected from the eastern side of unit B, we dated three segments. As expected, their ages exhibit a continuous increase with the depth into the wood. The oldest segment 4c was dated to 975 ± 30 BP and is 945 ± 25 yr old.

Architecture of Luna tree. Our long term research, based extensively on AMS radiocarbon dating, has revealed that all big African baobabs are multi-stemmed. The majority of baobabs start growing as single-stemmed trees. Over time, single-stemmed individuals become multi-stemmed owing to the baobabs' ability to produce periodically new stems, as other tree species produce branches. Typically, new stems shoot from the roots or emerge from fallen stems. Over time, the new stems may fuse with older stems or among them [17].

With a few exceptions, we investigated and dated the 50 largest known African baobab specimens, which are distributed in mainland Africa, African islands and Asia. In this respect, the Luna tree, with its very complex structure, was probably the most difficult to investigate and interpret of all big baobabs. The Luna tree consists of two fused units, each with a heavily buttressed base.

It has a large inner cavity with two rooms, which are inaccessible for people; the tree also has two big scars, one in each unit, due to severe damages in the past. There are several hollow parts in the wood of each unit and also several regrowth layers triggered by successive fire damage. There are buttressed roots all around the trunk and several "ornamental features" for a better anchorage. Consequently, it was difficult to find adequate sampling points in the trunk of Luna tree and, in addition, the collected wood samples were short.

It was, however, possible to determine the general architecture of Luna tree from the ages of the four segments extracted from sample 1, which originate from unit A (Table 1). The age sequence shows that the ages increase with the distance into the wood from the sampling point up to a point of maximum age (1b), after which they decrease toward the end of the sample, in the direction of the cavity. We identified and disclosed this anomaly, which is specific only to the closed ring-shaped structure, the most enigmatic architecture of the African baobab and of other baobab species. We also described the closed ring-shaped structure, which consists of several fused stems disposed in a ring, with an empty space inside. We termed this natural empty space between the fused stems as false cavity [17,19].

The Luna tree consists of two distinct units (A and B), which are fused up to a height of 3-4 m. The two units, which are very similar, have the same architecture, i.e., a closed ring-shaped structure. Consequently, in the case of Luna tree, we identified for the first time baobabs with two closed rings. We called this new architecture double closed ring-shaped structure.

Our research on baobabs evinced that the number of fused stems, which build the closed ring, varies between three and eight [17]. In principle, the number of stems can be determined from the analysis of radiocarbon dates of many samples collected from different areas of the tree, combined with a careful visual inspection of the false cavity, the trunk and the canopy for identifying stems and possible fusion lines [17,19]. In the case of Luna tree, due to the very high buttress and to the presence of hollow parts inside its trunk, the sampling was difficult, the samples were too short and their number was insufficient for an accurate determination of the number of stems which build each closed ring. However, after analysing the photographs of the Luna tree, taken from all directions, we can conclude that each unit is composed of four fused stems.

False cavities of Luna tree. In previous work, we described the false cavities and how they differ from normal/true cavities. Large normal cavities occur by wood removal, due to fungi decay, fire, animal or human damage; the pith/centre of the stem is located inside the cavity. False cavities are natural empty spaces between fused stems disposed in a closed ring-shaped structure. These empty spaces were never filled with wood. The oldest part of the fused stems is positioned between the false cavity walls and the outer part/exterior of each stem, always closer to the cavity. Normal cavities usually have irregular shapes and are not very tall (1.0–2.7 m). By contrast, false cavities are much larger and taller (3.0–8.3 m), have more regular shapes and their lower part is located at ground level. The first noticeable difference between false and normal cavities is the presence or absence of the bark inside the cavity. While normal cavities become larger over time due to continuous decay, false cavities become smaller because of stem growth [17,19]. The false cavities are associated with the presence of closed ring-shaped structures.

The described characteristics of false cavities fit very well the large inner cavity of Luna tree. The lower part is located at ground level (**Figure 5a**), its ceiling is very high (**Figure 5b**) and the cavity walls are covered by bark. As already mentioned, the Luna tree consists of two units, having each a ring-shaped structure. Each ring-shaped structure includes mandatory a false cavity between the fused stems. Consequently, the Luna tree includes two interconnected false cavities, rather than a false cavity with two connected rooms.

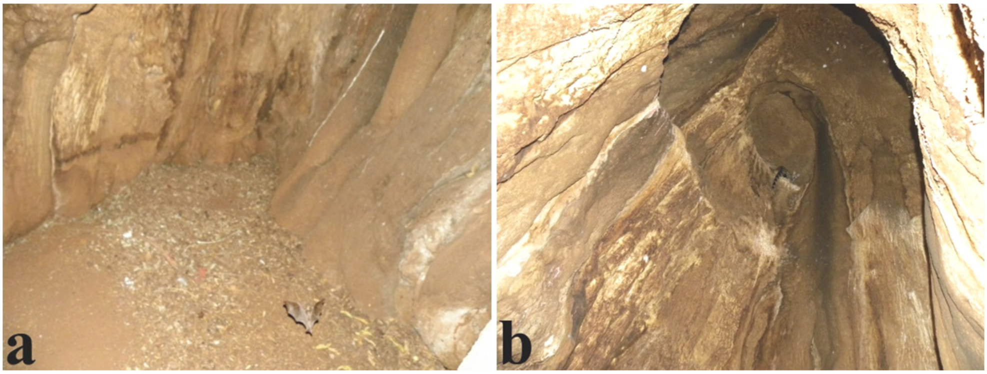

Figure 5. The images show the lower part of the inner false cavity in unit B (a) and the typical ceiling of the false cavity in unit A (b). One can notice that the walls of both cavities are covered by bark.

Age of Luna tree. One can state beyond any doubts that the age of the oldest part of Luna tree exceeds the age of the oldest dated sample segment 1b, i.e., 1405 ± 20 yr. This value corresponds to the point of maximum age of sample 1, which was collected from the large scar in unit A, located on the western side. However, the two rings are not yet completely closed, the still open part being the connection area of the two false cavities (**Figure 4**). We consider that the parent stem of the ring in unit A is located in the opposite direction to the still open part of the rings/false cavities, namely on the northern side. Because sample ages demonstrate that the growth of Luna tree was extremely slow over its life cycle, we estimate that the parent stem of the ring in unit A started growing at least 200 yr prior to the stem from which sample 1 originates. In this estimate, the Luna tree has an age of 1600 ± 100 yr. Thus, this baobab has started growing around AD 400.

The oldest dated sample segments collected from unit B are considerably younger, up to 945 ± 25 yr. This is probably a consequence of collecting short samples, given the presence of hollow parts in the wood; therefore, the points of maximum age were not reached. By considering that the two units and their canopies are quasi-similar, we consider that both units of Luna tree may have comparable ages.

CONCLUSIONS

Our research reports the results of the AMS radiocarbon investigation of Luna tree, a large African baobab from Venetia Limpopo Nature Reserve, South Africa. The research was performed for determining the architecture and age of the baobab. A number of four wood samples were collected from deep incisions in the trunk of Luna tree, which consists of two units and has a large inner cavity with two rooms. The age sequence of the dated segments from the oldest sample shows that ages increase with the distance into the wood up to a point of maximum age, after which they decrease toward the sample end. This anomalous age sequence is specific only to baobabs which have a multi-stemmed closed ring-shaped structure with a false cavity inside. In the case of Luna tree, each unit possesses such a closed ring. We also learned that the inner cavity with two rooms consists, in fact, of two interconnected false cavities. Consequently, for Luna tree, we identified for the first time a new architecture of the baobab, namely the double closed ring-shaped structure with two false cavities.

The radiocarbon date of the oldest sample segment was found to be 1507 ± 22 BP, which corresponds to a calibrated age of 1405 ± 20 yr. By considering the architecture of the baobab, we conclude that the oldest part of Luna tree has an age of 1600 ± 100 yr. By these values, the Luna tree becomes the fourth oldest African baobab with accurate dating results.

According to our research, the closed ring-shaped structure with a false cavity inside is seldom among African baobabs. Typically, this architecture enables baobabs to reach large sizes and old ages. We determined that the oldest dated specimen with single closed ring-shaped structure is the Lebombo Eco Trail baobab from Mozambique, with an age of 1400 yr [17].

In the current research, we identified a new architecture, that we named double closed ring-shaped structure with two false cavities. This architecture is exceptionally rare for baobabs and enables them to reach even older ages than the single ring-shaped structure, namely up to 1600 yr for Luna tree and 1750 yr for Holboom, a very large baobab from Namibia.

EXPERIMENTAL SECTION

Sample collection. The four wood samples were collected with a Haglöf CH 600 increment borer (60 cm long, 0.54 cm inner diameter). A number of small pieces/segments of the length of 0.1 cm were extracted from determined positions of the original four samples. These segments were processed and investigated by AMS radiocarbon dating.

Sample preparation. The standard acid-base-acid pretreatment method [21] was used for removing soluble and mobile organic components. The obtained samples were combusted to CO_2, via the closed tube combustion method [22]. Then, CO_2 was reduced to graphite on iron catalyst, under hydrogen atmosphere [23]. Finally, the resulting graphite samples were analysed by AMS.

AMS measurements. AMS radiocarbon measurements were performed at the NOSAMS Facility of the Woods Hole Oceanographic Institution (Woods Hole, MA, U.S.A.) by using the Pelletron ® Tandem 500 kV AMS system [24]. The obtained fraction modern values, corrected for isotopic fractionation with the normalized $\delta^{13}C$ value of $-25^0/_{00}$, were ultimately converted to a radiocarbon date.

Calibration. Radiocarbon dates were calibrated and converted into calendar ages with the OxCal v4.2 for Windows [25], by using the SHCal13 atmospheric data set [26].

ACKNOWLEDGMENTS

Authors thank De Beers Diamond Mining Company, Duncan MacFayden Research Centre and The South African National Parks for granting access in the reserve and for authorising the investigation of Luna tree. Authors also thank Diana Mayne, Thomas Huffman and Sarah Venter for support in the investigation and sampling of the baobab. The research was funded by the Romanian Ministry of National Education CNCS-UEFISCDI under grant PN-II-ID-PCE-2013-76.

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