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Investigation of the Architecture and Age of Superlative *Adansonia grandidieri* from the Andombiry Forest, Madagascar

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Abstract: Over the past years, our research on baobabs mainly focused on the largest Malagasy species, namely the Reniala or Grandidier baobab (*Adansonia grandidieri* Baill.). The biggest *A. grandidieri* are located in the Morombe area, especially in the so-called Andombiry Forest. This giant forest of Reniala hosts well over 6000 mature individuals, out of which more than 30 have very large sizes, i.e., circumferences over 20 m. We investigated, measured and dated by AMS radiocarbon the largest specimens. We found that all large Grandidier baobabs are multi-stemmed. They mostly exhibit a closed ring-shaped structure, with a false cavity inside. In this architecture, which enables Grandidier baobabs to reach very large sizes, the stems that build the ring typically have similar ages. Here we present the AMS radiocarbon investigation of two large baobabs, A 215 (girth 21.50 m) and A 257 (girth 25.70 m). According to dating results, the baobab A 215 has an age of only 375 years. It consists of four fused stems and has a closed ring-shaped structure. The baobab A 257 has the second largest trunk of all known live Reniala trees. It also exhibits a closed ring-shaped structure, with five fused stems around a false cavity, which has an opening toward the exterior. The dating results indicate that A 257 is around 900 years old.

Keywords: Madagascar; *Adansonia grandidieri*; radiocarbon dating; age determination; ring-shaped structure; false cavity

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1. Introduction

The genus *Adansonia* of the Bombacoideae subfamily in the Malvaceae family, comprises eight or nine species. Six of these species have a geographic range restricted to Madagascar [1–8].

In 2005, we initiated a scientific project for elucidating several aspects regarding the architecture, development and age of the African baobab (*Adansonia digitata* L.). This research relies on an approach, which does not only enable the investigation of dead or fallen trees, but also allows to investigate live, standing specimens. The original methodology consists of AMS (accelerator mass spectrometry) radiocarbon dating of tiny wood samples extracted from inner cavities, incisions in the trunk, fractured stems and from the exterior of the trunk/stems of monumental baobabs [9–16].

In 2013, we expanded our research to the most representative three Malagasy species, namely the za (*Adansonia za* Baill.), the fony (*Adansonia rubrostipa* Jum. and H. Perrier) and the Reniala or Grandidier baobab (*Adansonia grandidieri* Baill.) [17–21].

Over the past years, our research on baobabs mainly focused on the most famous species of Madagascar, namely the Reniala (in Masikoro, i.e., "Mother of the Forest"). According to the classical description, the Grandidier baobabs are presented as large trees with columnar trunks, flat-topped crowns and quasi-horizontal large branches [2]. However, the dimensions and shape of mature and old individuals may vary substantially, and the differences depend especially on the location. Thus, the specimens in the Morondava area, where the famous Avenue of Baobabs is located, are tall and rather slim (with heights up to 25–30 m and circumferences around 8–13 m), while the Andavadoaka area is dominated by bottle baobabs resembling corpulent dwarfs (with heights of 4–10 m and circumferences up to 10–13 m) and have trunks with many hollows (like a slice of Emmenthaler). The largest *A. grandidieri*, which have very massive trunks (with heights of 12–18 m and circumferences up to 29 m), are located close to Morombe, in the so-called Andombiry Forest.

We found, somewhat surprisingly, that the largest *A. grandidieri*, in terms of wood volume, are bigger than the largest *A. digitata* from mainland Africa. Thus, one can state that the Grandidier baobab is the biggest of all *Adansonia* species [20,21].

Like the African baobabs, the very big Reniala are always multi-stemmed. Our research on African baobabs has determined a novel type of architecture that allows for them to reach very large dimensions and old ages. In this very unexpected and idiosyncratic architecture, multiple stems are disposed in a circular or elliptical pattern, enclosing an empty space between them; we coined it ring-shaped structure (RSS). The most frequently occurring is the closed RSS, in which the multiple stems are pointed upward and are almost perfectly fused together. The fused stems describe a ring at ground level with an empty space inside, which was never filled with wood. This natural empty space was termed false cavity. According to radiocarbon dating results, closed RSSs form progressively and close over time [12,14,17,18].

Unlike African baobabs with closed RSSs, which usually have irregular shapes, sometimes with stems growing outside the ring, the Grandidier baobabs with this architecture have trunks with a relatively regular shape. Thus, the multi-stemmed trunk may have the shape of a flat-bottomed egg or of a bell jar. In other cases, the trunk has, in at least one direction, the shape of a bell jar or of a bottle, while from the other directions it looks cylindrical. As for African baobabs, the false cavities of *A. grandidieri* trees, which are also covered by bark, may have one or several openings toward the exterior or, in many cases, all such openings are already closed. According to radiocarbon results, the ring of Grandidier baobabs is composed of stems of similar ages.

As mentioned, the largest *A. grandidieri* are found in the Andombiry Forest. The forest has a quasi-trapezoidal shape and is bounded by four villages: Andombiry, Belitsaka, Ankoabe and Isosa. It has a total surface of almost 100 km^2 and hosts 6000 mature individuals, out of which more than 30 are superlative baobabs, with circumferences over 20 m [21].

In two previous articles, we disclosed the radiocarbon dating results of three superlative Reniala specimens from the Andombiry Forest, namely the famous Tsitakakoike, which toppled and died in 2018–2019, the Pregnant baobab and the Big Reniala of Isosa [18,21].

Here we present the result of our investigation and AMS radiocarbon dating of two other very large specimens from the Andombiry Forest, i.e., the Grandidier baobabs which we named A 257 and A 215. The aim of the research was to ascertain the following: (i) What are the ages of the investigated baobabs, recte the age of the oldest part of each tree? (ii) Do the investigated baobabs have an inner cavity? If so, is it normal or false? (iii) What architecture do the studied baobabs exhibit? In the case of monumental multi-stemmed baobabs, the answers to these questions can only be determined by using radiocarbon dating.

2. Materials and Methods

2.1. The Two Baobabs and Their Areas

The two superlative Grandidier baobabs A 257 and A 215 can be found in the dry deciduous Andombiry Forest, in the Morombe district, Atsimo-Andrefana region of southwestern Madagascar. The mean annual rainfall of the area is 458 mm (Morombe station).

The A 257 baobab (A from Andombiry, 257 from the girth value of 25.70 m) is located in the proximity of a dirt road connecting the villages of Isosa and Andombiry, at a distance of 8 km from Isosa and 2 km from Andombiry. Its GPS coordinates are 21°34.804′ S, 043°30.424′ E and the altitude is 8 m (Figure 1). A 257 has a maximum height of 18.5 m and the circumference at breast height (cbh; at 1.30 m above ground level) is 25.70 m (Figure 2). It has an overall wood volume of 460 m^3. After the demise of Tsitakakoike, A 257 has the second largest circumference of all live Grandidier baobabs (the record holder Tsitakakantsa, with a girth of 28.90 m, is located at a distance of only 1.3 km).

Figure 1. Map of Madagascar (**A**) with a detail of the investigated area, showing also the positions of the two baobabs in the red square (**B**).

Figure 2. General view of the A 257 baobab taken from the northwest.

The huge trunk exhibits a closed RSS, which consists of five perfectly fused stems around a false cavity. The trunk forks at heights of 8.7–10.2 m along the circumference. Many large Reniala from the Andombiry Forest do not correspond to the classical description of Grandidier baobabs, which implies flat-topped crowns with quasi-horizontal large branches. Thus, A 257 has the majority of its branches directed upward, while some of them are directed toward the ground (Figure 3).

Figure 3. Photo of A 257 from the north, showing its branches pointed upward, while some are directed toward the ground.

The trunk is columnar, except for its eastern side where it has the shape of a bell jar (Figure 4). This general appearance of the tree is specific to Grandidier baobabs with closed RSS. The false cavity has an opening toward the exterior, which is not accessible to humans. According to locals, the opening was enlarged by honey gatherers. The opening, located on the southern side of the trunk, which has a somewhat triangular shape, is situated at a height of 0.81 m above the ground. Its maximum width is 0.40 m and the height reaches 0.68 m (Figure 5A). The walls of the false cavity have a thickness of 1.46 m at the opening, while its inner diameter is around 3.75 m (at a height of 1 m). The false cavity has a bell shape and a height of around 10 m, up to the forking area of the trunk. The walls of the false cavity are covered by bark (Figure 5B).

Figure 4. Image of A 257 presenting its eastern side with the shape of a bell jar.

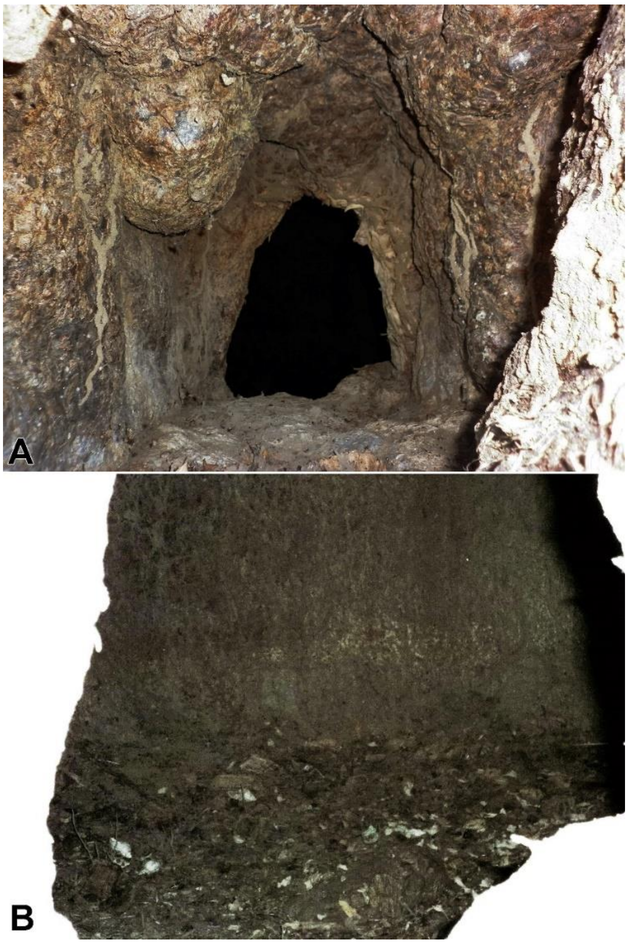

Figure 5. The entrance to the false cavity of A 257 (**A**). The exterior of the entrance (**B**). The interior of the false cavity illuminated with a flashlight.

The horizontal dimensions of the canopy, which has branches with diameters up to 2.2 m, are 29.2 (WE) × 22.5 m (NS). Due to its old age, A 257 no longer produces pods.

The A 215 baobab (A from Andombiry, 215 from the girth value of 21.50 m) can be found in an area of the forest with a lower density of trees and shrubs. It is located close to another dirt road, between the villages of Belitsaka and Andombiry, at a distance of 5 km from Belitsaka and 9 km from Andombiry. Its GPS coordinates are 21°38.317′ S, 043°31.222′ E and the altitude is 11 m. A 215 has a maximum height of 16.2 m and the circumference at breast height is 21.50 m (Figure 6). It has an overall wood volume of 320 m^3.

Figure 6. General view of the A 215 baobab from the northwest.

The trunk exhibits a closed RSS, which is composed of four perfectly fused stems around a false cavity. The false cavity is completely closed, without any opening toward the exterior. The trunk forks at heights of 9.7–10.8 m along the circumference. This trunk is cylindrical, with the exception of one side where it has the shape of a bell jar (Figure 7).

Figure 7. Photo of A 215 showing its southwestern side, which has a bell jar shape. The horizontal dimensions of the canopy are 22.8 (WE) × 16.7 m (NS).

2.2. *Investigation of the Two Baobabs*

2.2.1. Wood Samples

Two wood samples, labeled A 257-1 and A 257-2, were collected from the trunk of the A 257 baobab on either side of the entrance to the cavity, both at a height of 1.33 m above ground. The lengths of the two samples were 0.75 and 0.29 m. A total of six tiny segments (marked from a to f), each of the length of 1 mm, were extracted by using a sterile scalpel from predetermined positions of sample A 257-1. The segments were processed and dated by AMS radiocarbon. Sample A 257-2 was considered too short for investigation.

Two other wood samples, labeled A 215-1 and A 257-2, were collected from the trunk of the A 215 baobab, at heights of 1.56 and 1.40 m above ground. The length of the two samples were 0.26 and 0.78 m. Sample A 215-1 was short and, therefore, we investigated only sample A 215-2. A total of four tiny segments (marked from a to d), each of the length of 1 mm, were extracted from predetermined positions of sample A 215-2. These segments were also processed and dated by AMS radiocarbon.

The wood samples were collected with a Haglöf CH 800 increment borer (0.80 m long, 0.0108 m inner diameter) and wrapped in tin foil until the subsequent selection of the segments for dating (Figure 8). After each coring, the increment borer was cleaned and disinfected with methyl alcohol. The small coring holes were sealed with Steriseal (Efekto), a special polymer sealing product, for preventing infection.

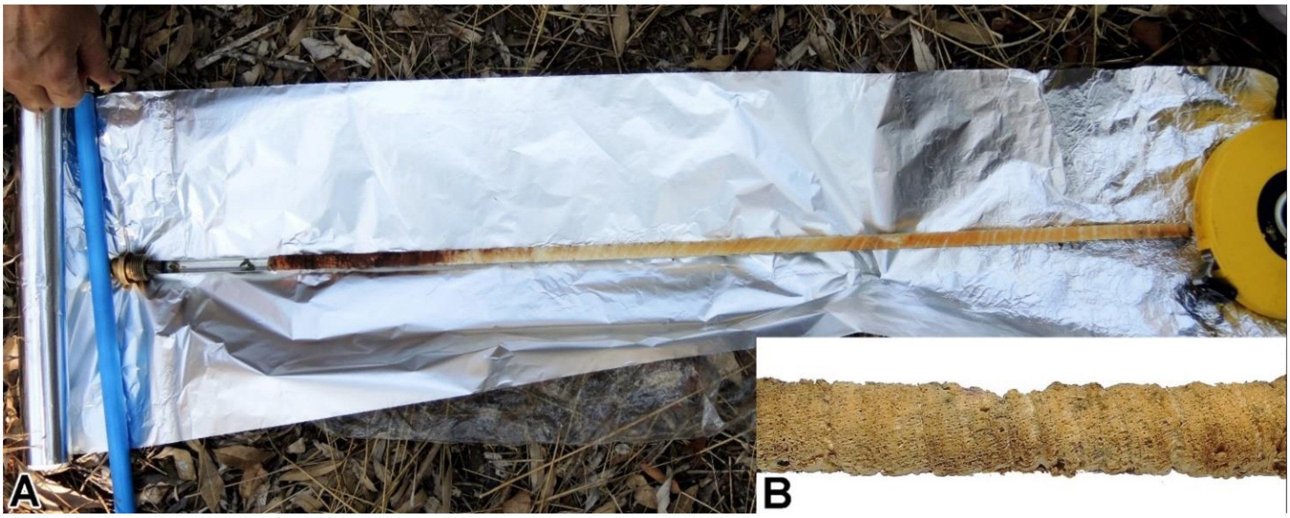

Figure 8. Photo showing sample A 257-1 being extracted from the increment borer to be wrapped in tin foil until further investigation (**A**). Detail of sample A 257-1, showing the growth rings, which typically become obvious 7–10 days after sampling (**B**).

2.2.2. Sample Preparation

The α-cellulose pretreatment method was used for removing soluble and mobile organic components [22]. The resulting samples were combusted to CO_2, which was next reduced to graphite on iron catalyst [23,24]. The graphite samples were investigated by AMS.

2.2.3. AMS Investigation

The radiocarbon measurements were performed at the AMS Facility of the iThemba LABS, Johannesburg, Gauteng, South Africa, using the 6 MV Tandem AMS system [25]. The obtained fraction modern values were finally converted to a radiocarbon date. The radiocarbon dates and errors were rounded to the nearest year.

2.2.4. Calibration

Radiocarbon dates were calibrated and converted into calendar ages with the OxCal v4.4 for Windows [26], by using the SHCal20 atmospheric data set [27].

3. Results

3.1. Radiocarbon Dates and Calibrated Ages

Radiocarbon dating results of the six sample segments, which originate from sample A 257-1, as well as of the four sample segments, which originate from sample A 215-2, are presented in Table 1. The radiocarbon dates are expressed in ^{14}C yr BP (radiocarbon years before present, i.e., before the reference year 1950). Radiocarbon dates and errors were rounded to the nearest year.

Table 1. Radiocarbon dating results and calibrated ages of sample segments collected from the A 257 and A 215 Grandidier baobabs.

Sample/ Segment Code	Depth [1] (Height [2]) (m)	Radiocarbon Date (Error) (^{14}C yr BP)	Cal CE Range 1σ (Confidence Interval)	Assigned Year (Error) (cal CE)	Sample/Segment Age (Error) (cal CE)	Accession Number
A 257-1a	0.10 (1.33)	98 (±40)	1708–1720 (6.7%) 1812–1836 (16.8%) 1852–1866 (7.5%) **1880–1926 (37.3%)**	1903 (±25)	120 (±25)	IT-C-2229
A 257-1b	0.20 (1.33)	207 (±24)	1671–1688 (15.0%) **1730–1782 (43.9%)** 1792–1802 (9.4%)	1756 (±25)	265 (±25)	IT-C-2693
A 257-1c	0.35 (1.33)	361 (±23)	1505–1518 (9.8%) **1524–1592 (50.6%)** 1618–1628 (7.8%)	1558 (±35)	465 (±35)	IT-C-2699
A 257-1d	0.50 (1.33)	477 (±39)	**1426–1484 (68.3%)**	1455 (±30)	565 (±30)	IT-C-2215
A 257-1e	0.60 (1.33)	625 (±22)	**1324–1346 (45.4%)** 1391–1402 (22.8%)	1335 (±10)	685 (±10)	IT-C-2705
A 257-1f	0.75 (1.33)	923 (±30)	**1152–1214 (68.3%)**	1183 (±20)	860 (±20)	IT-C-1682
A 215-2a	0.20 (1.40)	126 (±23)	1710–1718 (6.0%) 1813–1836 (18.6%) 1855–1866 (6.5%) **1880–1925 (37.2%)**	1902 (±20)	120 (±20)	IT-C-2701
A 215-2b	0.45 (1.40)	220 (±27)	1668–1680 (10.1%) **1734–1785 (49.4%)** 1792–1802 (8.7%)	1770 (±25)	250 (±25)	IT-C-2704
A 215-2c	0.65 (1.40)	269 (±30)	**1640–1672 (40.6%)** 1743–1763 (6.4%) 1765–1772 (4.8%) 1780–1797 (16.4%)	1656 (±15)	365 (±15)	IT-C-2230
A 215-2d	0.78 (1.40)	206 (±29)	1669–1692 (16.7%) **1727–1784 (41.3%)** 1794–1808 (10.3%)	1755 (±30)	265 (±30)	IT-C-2711

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

Calibrated (cal) ages, expressed in calendar years CE (CE, i.e., Common Era), are also displayed in Table 1. The 1σ probability distribution (68.3%) was selected to derive calibrated age ranges. For two segments (A 257-1d, A 257-1f), the 1σ distribution is consistent with one range of calendar years. For one segment (A 257-1e), the 1σ distribution corresponds to two ranges of calendar years, while for four segments (A 257-1b, A 257-1c, A 215-2b, A 215-2d) it corresponds to three ranges. Finally, for the other three segments (A 257-1a, A 215-2a, A 215-2c), the 1σ distribution is consistent with four ranges of calendar years. In all these cases, the confidence interval of one range is considerably greater than that of the other(s); therefore, it was selected as the cal CE range of the segment for the purpose of this discussion. In all cases, the selected age range is marked in bold in Table 1.

We derived an assigned year for each sample segment, which corresponds to the mean value of the selected age range, with the error rounded to the nearest 5 yr. Sample segment ages, expressed in calendar years, represent the difference between the year 2021 CE and the assigned year. Sample ages and errors were rounded to the nearest 5 yr. We used this approach for selecting calibrated age ranges and single values for sample/segment ages in our previous articles on AMS radiocarbon dating of large angiosperms, especially baobabs [9–16,20].

3.2. Sample Ages

For the six dated sample segments of sample A 257-1, which was extracted from the outer part/exterior of the southern side of the trunk of the A 257 baobab, segment ages increase with the depth into the wood, i.e., from A 257-1a to A 257-1f.

The youngest segment A 257-1a, which originates from a distance of 0.10 m from the exterior, has a radiocarbon age of 98 ± 40 BP, which translates to a calibrated age of 120 ± 25 calendar yr. This value shows that the A 257 baobab was not affected by the growth stop phenomenon and is still growing [13]. The oldest segment A 257-1f represents the sample end, which is situated at a depth of 0.75 m in wood. The calibration of its radiocarbon age of 923 ± 30 BP corresponds to 860 ± 20 calendar yr. The increasing sample age sequence shows that the sampling process did not reach the point of maximum age located further inside the false cavity walls.

In the case of the four sample segments originating from sample A 215-2, which was collected from the outer part/exterior of the northwestern side of A 215 baobab, ages increase with the depth in wood only for the first three segments, from A 215-2a to A 215-2c.

The oldest segment A 215-2c, which originates from a distance of 0.65 m into the wood, has a radiocarbon age of 269 ± 30 BP, which translates to a calibrated age of 365 ± 15 calendar yr. The deepest segment A 215-2d, which represents the sample end at a distance of 0.78 m into the wood, is younger. Its radiocarbon date of 206 ± 29 BP is consistent with a calibrated age of 265 ± 30 calendar yr. The sample age sequence shows that in this case the sampling process has reached the point of maximum age, which is located close to the point from which segment A 215-2c originates.

4. Discussion

4.1. Architecture of the Two Baobabs

Many very large and/or old trees of the *Adansonia* genus exhibit closed RSSs. The closed RSS, which incorporates a false cavity, was first identified for *A. digitata* [12] and later confirmed for *A. za* [19] and *A. grandidieri* [18]. In this architecture, dating results reveal an anomalous age sequence for samples collected from the exterior toward the false cavity, as well as from samples collected from the cavity walls toward the exterior.

A few other Grandidier baobabs investigated by radiocarbon have a different type of architecture, namely a cluster structure in which multiple stems are perfectly fused together. Thus, the Giant of Bevoay [20] and the Big Reniala of Isosa, which is the record holder in terms of volume for the *Adansonia* genus (540 m^3) [21] consist of three and five stems, respectively.

For the baobab A 215 the age sequence of segments along the investigated sample is anomalous, namely it is characteristic for the presence of a false cavity. Consequently, the baobab A 215 has a closed RSS with a false cavity, which is completely closed.

In the case of baobab A 257, the large central cavity is visible and has an opening. However, according to the dating results of the investigated sample, the point of maximum age was not reached. In this case, in order to discriminate between a normal cavity (resulted by wood decay) and a false cavity (an empty space that never contained wood) it is necessary to extrapolate the age of the oldest dated segment to the presumptive pith, which is located in very different positions in the two possible scenarios.

Thus, if the cavity were a normal one, the position of the presumptive pith would be close to the center of the multi-stemmed trunk, and consequently, to that of the large inner cavity, which is also quasi-symmetrical. We found that the oldest segment, which originates at a distance of 0.75 m from the exterior of the trunk (at a height of 1.33 m), has an age of around 860 years. The girth of the trunk is 25.70 m, which corresponds to a diameter of 8.20 and a radius of 4.10 m. By extrapolating the age of the oldest dated sample to the center of the trunk and of the cavity, an age over 3000 years would be obtained. Such a high age value is impossible for a Grandider baobab.

If the cavity is a false one, the point of maximum age is located inside the false cavity walls, which are 1.46 m thick, always closer to the cavity than to the exterior of the tree [12,14]. In this case, the age calculated by extrapolation from the oldest segment of sample A 257-1 is around 900 years (see Section 4.2.), which represents a realistic value. Thus, we demonstrated that the cavity of A-257 is a false one and the architecture is a closed RSS.

4.2. Age of the Two Baobabs

The age of the two investigated baobabs was calculated by extrapolating the age of the oldest dated segment to the point of maximum age inside the cavity walls, in the sampling direction and at sampling height. As mentioned, the point of maximum age is located inside the false cavity walls, always closer to the cavity than to the exterior of the tree.

The measured cavity walls of the A 257 baobab are 1.46 m thick. The oldest segment of sample A 257-1, collected in the proximity of the cavity opening, i.e., A 257-1f, has an age of 860 $\pm$ 20 calendar yr. It originates from a distance of 0.75 m from the exterior and, consequently, at 0.71 m from the inner cavity. These distances show that the point of maximum age must be situated in close proximity, probably at a few centimeters toward the cavity. Therefore, we consider that the age of A 257 baobab is 900 $\pm$ 50 years. Consequently, A 257 started growing around the year 1120 CE.

In the case of sample A 215-2, we specified that, according to the age sequence of segments, the point of maximum age is situated very close to the position of the oldest dated segment, A 215-2c. This segment was found to have an age of 365 $\pm$ 15 calendar yr. Thus, we consider that the age of A 215 baobab is 375 $\pm$ 25 years. One can state that A 215 started its growth around the year 1650 CE.

According to our research, the monumental Grandidier baobabs from the Andombiry Forest may have very different ages, ranging from 375 years (A 215) to 1400 years (the deceased Tsitakakoike). At 900 years, A 257 is one of the oldest baobabs in the forest.

Radiocarbon dating results have identified three *Adansonia* species that can live over 1000 years: the Granidier baobab (1400 yr) [18], the fony baobab (1600 yr) [17] and the African baobab (2500 yr) [14], which is also the oldest angiosperm.

There is a paucity of ample studies on ages of other tropical trees. In 1998, Chambers et al. [28] reported ages of over 1000 years for two tropical trees of the Amazonian rain forest, with values up to 1400 years for a *Cariniana micrantha* specimen. This study was based on single samples of each tree and on single radiocarbon measurements. Furthermore, their findings contradict other studies on the age limit of similar tree species from the Amazonian rain forest and were questioned by several researchers [29–31].

In 2012, Kinahan presented a report on the ages of live and dead camelthorn trees (*Vachellia erioloba*) from Namibia, determined by radiocarbon dating. The radiocarbon dating results, which mention ages up to almost 1000 years, were published in 2016 [32].

To the best of our knowledge, no other angiosperm exceeding 1000 years with accurate dating results has been identified. Typically, the inner and oldest radiocarbon-datable material in such old trees is usually missing due to decomposition processes leading to relatively young ages of several centuries [33]. Among the very few radiocarbon age assessments of tropical trees, we would like to mention the oldest species: the Za baobab (*A. za*; 900 yr) [19], the tea tree (*Camellia sinensis*; 700 yr) [34] and the Ceylon iron wood (*Manilkara hexandra*; 550 yr) [35].

5. Conclusions

Our research presents the investigation of the age and architecture of two very large Grandidier baobabs, named A 215 and A 257, from the Andombiry Forest located within Morombe area in southwestern Madagascar. Both baobabs are multi-stemmed and exhibit a closed ring-shaped structure, with a false cavity inside. The false cavity of A 215 is completely closed, while the cavity of A 257 has an opening toward the exterior. Wood samples collected from the two baobabs were dated by AMS radiocarbon. The baobab A 215 (girth 21.50 m) is composed of four perfectly fused stems. The oldest dated sample had a radiocarbon date of 269 $\pm$ 30 BP, which corresponds to a calibrated age of 365 $\pm$ 15 years. The baobab A 257 (girth 25.70 m), which has the second largest trunk of all live Grandidier baobabs, consists of five fused stems. The oldest sample had a radiocarbon date of 923 $\pm$ 30 BP, corresponding to a calibrated age of 860 $\pm$ 20 years. The extrapolation of the oldest dated samples to the corresponding points of maximum age indicate that the age of the baobab A 215 is close to 375 years, while the baobab A 257 is 900 years old.

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