“BABEȘ-BOLYAI” UNIVERSITY CLUJ-NAPOCA
Faculty of Biology and Geology
Doctoral School of Integrative Biology

-Ph.D. Thesis Summary-

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The investigation of some superlative baobabs (*Adansonia* spp.) by AMS radiocarbon dating for assessing the ages, architecture and growth rates, and by stable isotope analysis respectively, for climate study

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Abbreviations and explained terms:

AMS – Accelerator Mass Spectrometry

stem – word used in the present thesis with the following meaning: a tree can have multiple stems, but only one trunk. A tree tunk consists of at least one stem

IUCN – International Union for Conservation of Nature

cbh – Circumference at breast height, namely at the standard height of 1.30 m above the ground

N/A – not available

IPCC – Intergovernmental Panel on Climate Change

SST – Sea Surface Temperature

ENSO - El Niño–Southern Oscillation

TTT – Tropical Temperate Troughs

LIA – Little Ice Age

MWP – Medieval Warm Period

CE – Common Era used instead of **AD** (Anno Domini)

BCE – Before Common Era used instead of **BC** (Before Christ).

LTSB – long triangular stem buttress, alternative name for false stem

Keywords: baobabs; superlative trees; age determination; ring-shaped structures; false cavities; paleoclimate reconstruction; radiocarbon dating; stable isotope analysis; stem architecture; tropical trees

Chapter I. Introduction

1. Objectives

This Ph.D. thesis represents a continuation of the research on the age, growth and architecture of the African baobab, which was started in 2005. The initial objectives followed three main questions:

i) Are African baobabs centennial or millennial trees?

ii) Why are there significant architecture differences between baobabs?

iii) Why are certain cavity walls covered by bark while others are not?

To answer these questions a modern and original methodology was developed, which is based on AMS (accelerator mass spectrometry) radiocarbon dating of very small wood samples. These complex investigations revealed that the members of the *Adansonia* genus are trees with unique traits, that were not identified for any other plant species. Thus, the aim of the Ph.D. thesis was the continuation of the radiocarbon dating of monumental baobabs to which a new component was added, namely the stable isotope analysis for past climate reconstruction. The new questions and objectives of this research presented within the Ph.D. thesis are the following:

i) What is the maximum stem number the African baobab can have?

ii) Why do some stems exhibit triangular or trapezoid shapes in longitudinal section?

iii) Why are the outermost rings, closest to the bark, very old instead of being very young?

iv) Which is the oldest baobab alive with accurate dating results?

v) Which is the largest boabab alive in terms of volume?

vi) The radiocarbon dating of the most famous African baobab (Chapman baobab) and identifying the factors that contributed to its untimely demise.

vii) What is the upper age limit of the African baobab?

viii) Performing the past climate reconstruction for central Botswana for the last millennium by using the Chapman baobab as rainfall proxy;

ix) Verifying the aridification trend for Botswana;

x) Verifying the hypothesis of the tropical temperate throughs movement to the east in the past;

xi) What caused the demise of monumental baobas in southern Africa?

2. *Adansonia* genus

2.1. Overview.

The name of the genus was established by Carl von Linné, who called it *Adansonia* in the honor of Michel Adanson, who scientifically described the African baobab for the first time (Linnaeus, 1753; 1759). The word *digitata* was inspired by the palmately compound leaves, which resemble the human fingers (Adanson, 1761).

The baobab belongs to the Malvaceae family, which is a part of the Bombacoideae subfamily, Adansoniae tribe, spongy endocarp clade (Carvalho-Sobrinho et al., 2016).

Some common morphological aspects of baobabs are a relatively large massive bottle-shaped trunk and a compact canopy. The soft wood fibers can store a large quantity of water (Guy, 1970; Wickens and Lowe, 2008). The baobab is considered a stem succulent-tree, a name given to the functional group of tropical trees distributed in arid and semi-arid areas, which exhibit a strong stomatal control to avoid water loss (Chapotin et al., 2006a, 2006b; De Smedt et al. 2012; Rutherford et al., 2018).

Next to its ability to store water in their trunks, such trees and perform the so-called stem recycling photosynthesis at no additional water cost (Cernusak and Cheesman, 2015; Ávila-Lovera and Ezcurra, 2016). Accessing and recycling resources available at local level improves the resistance to drought and is an adaptation to arid and semi-arid conditions.

2.2. Cladistics, species, distribution, uses and conservation.

The *Adansonia* genus has an almost exclusively tropical distribution and is represented by 8 or 9 species, namely: *A. gregorii* syn. *gibbosa* F. Mull./A. Cunn. on the Australian continent, 6 species endemic to Madagascar (*A. madagascarensis* Baill., *A. grandidieri* Baill., *A. suarezensis* H. Perr., *A. perrieri* Capuron, *A. za* Baill., *A. rubrostipa* Jum. and H. Perr.) and 1-2 species in continental Africa (*A. digitata* L. and *A. kilima* Pettigrew et al.) The genus was dispersed throughout the subtropics (Wickens 1983, Wickens and Lowe 2008, Bell et al., 2015).

In 2012, after new genetic and morphological evidence, Pettigrew et al. described a new diploid species called *A. kilima*. This species was identified in Zambia Tanzania Kenya Namibia and South Africa but Cron et al. (2016) contradicts this finding and suggest a very high intraspecific diversity instead. In this paper both species are presented under the common name of African baobab.

Cladistics. The morphological flower differences led to the classification of baobabs into 3 different sections (Hochreutiner 1908). This classification was revised (Baum, 1995) and confirmed at genetical level (Baum et al., 1998). The 3 sections are *Adansonia* section *Brevitubae*

Hochreutiner, *Adansonia* section *Longitubae* Hochreutiner and *Adansonia* section *Adansonia* Hochreutiner (Hochreutiner, 1908; Baum, 1995; Baum et al., 1998; Pettigrew et al., 2012).

2.2.1. Adansonia section Brevitubae. This section comprises the species *A. suarezensis* and *A. grandidieri*.

A. suarezensis has a distribution restricted to the north of Madagascar (72 km^2), in areas with calcareous soils and deciduous forests (Baum, 1995; Madagascar Catalogue, 2018; IUCN, 2019). Suarez's baobab was included in the endangered category (EN) in 2015 according to IUCN.

A. grandidieri has a natural distribution on a 20.000 km^2 area in the south-west of the island. Grandidier baobab is one of the most representative Malgasy trees. The species evaluated in 2016 is also included in the endangered category (EN) (Ravaomanalina and Razafimanahaka, 2016).

In 2018, the largest and oldest Grandidier baobab called Tsitakakoike collapsed after 3 years of protracted drought. The first rainfall occurred in the 2018-2019 rainy season and led to severe floods. Recently, another Grandidier baobab that was measured became the largest angiosperm in the world (see chapter V; Patrut R.T. et al., 2019). This monumental specimen is located close to the giant Tsitakakoike (total volume 520 m^3). By the radiocarbon determined age of Tsitakakoike (1400 ± 100 years), the Grandidieri baobab became the third millennial angiosperm in the world (Patrut A. et al., 2015b).

2.2.2. Adansonia section Longitubae. This section comprises the species *A. rubrostipa, A. madagascariensis, A. za., A. perrieri* and *A. gregorii*.

A. rubrostipa can be found on the western coast of Madagascar, on an area covering 20.000 km^2. According to a IUCN revision of 2018, it is included in the least concern category (LC) (Letsara et al., 2019b).

In 2015, *A. rubrostipa* became the second millennial baobab species of the world with accurate dating results of the specimen Grand-mère, which is located in the Tsimanampetsotsa National Park. The age was found to be 1600 years (Patrut A. et al., 2015c).

A. madagascariensis naturally distributed on an area of ca. 35.000 km^2, ranging from the Ambongo region (north-west) to Antsiranana (north). According to IUCN, *A. madagascariensis* is listed as a near threatened species (NT) since 1998 (World Conservation Monitoring Centre, 1998a).

A. za can be found in western Madagascar, from the south of the island up to the north of the western coast, covering a vast area of about 130.000 km^2. This species plays a vital traditional role of a cistern for the Mahafaly population. The za baobab is in the least concerned category (LC) (Letsara et al., 2019c). The largest za baobab is Anzapalivoro (in Mahafaly „sacred za, palace of birds"), which has an age of ca. 900 years, the height 26,3 m and circumference 22,25 m.

A. perrieri is a forest species that has the lowest number of individuals ca. 152-250. It is restricted to the north of Madagascar, between the Ankarana peak (Massif d'Ankarana) to the south and the Fort d'Ambre reserve to the north. According to IUCN, *A. perrieri* is critically endangered (CR) (Letsara et al., 2019a).

A. gregorii is distributed in the Kimberley region of Western Australia and in the proximity of Victoria river in Northern Territory. According to IUCN 2019 update, the population is stable and belongs to the least concern category (LC) (BGCI and IUCN, 2019).

2.2.3. Adansonia section Adansonia. This section comprises the species *A. digitata and A. kilima*.

The African baobab has a natural distribution throughout sub-Saharan Africa, and is usually found in semi-arid areas. Its tolerance range is very high, the trees can grow on any substrate, even on granite (Slotta et al., 2017).

The African baobab has over 300 documented uses (Gebauer et al., 2016) and is an important medicinal plant that is also regarded as a valuable superfood (Vincenzo, 2013). Every part of the baobab has multiple uses. Its remarkable regeneration capacity allows even ringbarked trees to survive and regenerate the bark in time (Wickens and Lowe, 2008; Kotina et al., 2017). The African baobab is the oldest angiosperm ever dated (Patrut A. et al., 2018).

The taxon is not registered in the IUCN Red List and can be considered a cosmopolitan species (Cuni Sanchez et al., 2010; IUCN, 2019).

The African baobab (*A. digitata)* is the angiosperm with the largest circumference ever recorded by the Holboom specimen (cbh = 35,10 m). The African baobab is the second largest angiosperm in terms of volume (after *A. grandidieri*) by the Platland/Sunland baobab, whose volume reached 501 m^3 (Patrut A. et al., 2011; Patrut A. et al., 2017b).

3. Radiocarbon dating: Application in dendrochronology

In 2005, a research team led by Adrian Patrut began an in-depth investigation of the *Adansonia* genus by an original methodology (Patrut A. et al., 2007; 2010c; 2011; Patrut R.T., 2013; 2015a), which enabled direct sample extraction from standing live trees and the radiocarbon dating of the wood samples. Thus, in 2007, Patrut A. et al. AMS radiocarbon dated the first monumental African baobab called Grootboom („large tree" in Afrikaans). This baobab from Namibia became th first millennial angiosperm with accurate dating results (Patrut A. et al., 2007).

AMS radiocarbon dating is the only way of ascertaining the age of monumental trees, i.e. very old and/or large trees.

Chapter II. Methodology

Metric measurements, such as the height, circumference at breast height (cbh, namely at 1.30 m above the ground) and the total wood volume were accurately determined. Measurements of other researchers or authors were also used as reference or for comparisons.

Samples were extracted from interior cavities and/or the outer part(s) of the stems at convenient and accessible heights or from collapsed and/or broken stems or branches (Fig. 1). Sampling was performed with a Haglöf increment borers of various lengths between 0.60-1.50 m. After every coring, the borer was cleaned and disinfected. The small coring holes were immediately sealed to prevent any infection.

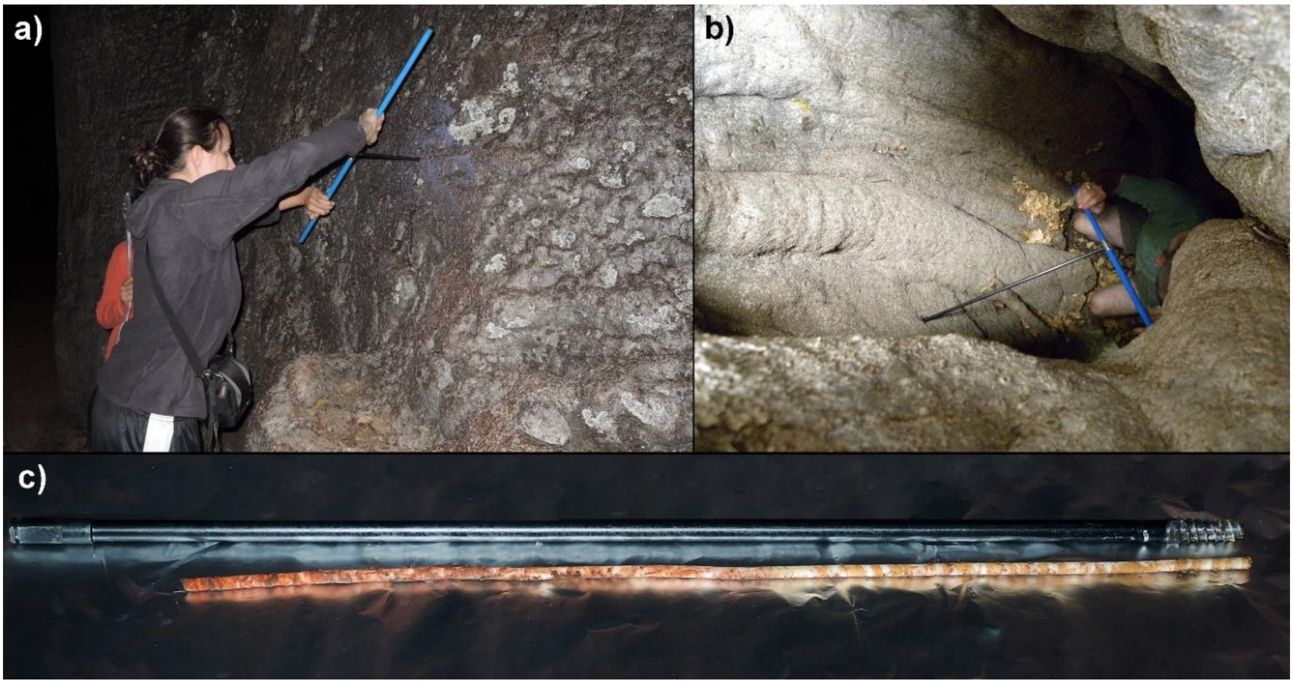

Figure 1. Sample extraction by a Haglöf increment corer out of the exterior of a baobab trunk (a) and out of the walls of a false cavity (b). The wood sample is placed next to the corer for comparison (c).

For age determination, 0.001 m long **segments were selected** from predetermined positions of the samples. The segments were pretreated and subsequently radiocarbon dated.

Selected wood samples followed 3 **preparation steps** prior to AMS radiocarbon dating:

i) pretreatment for celullose extraction;

ii) cellullose combustion to CO_2;

iii) CO_2 conversion to graphite.

AMS radiocarbon measurements were finally performed on the resulting graphite samples.

The result of the AMS measurement is a fraction carbon modern value. The radiocarbon age, expressed in years ^{14}C BP (radiocarbon years before present, namely before the reference year 1950), is calculated by the corrected $\delta^{13}C$ value of the fraction modern (Fm) as follows:

Radiocarbon age = -8033 ln(Fm)

The radiocarbon age error is calculated by the multiplication of the relative Fm error with 8033. Radiocarbon ages and errors were rounded to the nearest year.

For obtaining calendar ages, a **calibration** of the radiocarbon age is performed (Stuiver and Polach, 1997). For this purpose, an appropriate calibration curve must be selected. In this thesis, radiocarbon ages were converted to calibrated age ranges with the OxCal 4.3 program (Bronk Ramsey, 2009). The atmospheric data sets SHCal13 (Hogg et al., 2013), IntCal13 (Reimer et al., 2013) and Bomb SH1-2 (Hua et al., 2013) were used.

Calibrated age ranges are expressed in cal CE, (calibrated years Common Era). For obtaining calibrated age ranges the 1σ (68,2%) and/or 2σ (95,4%) probability distribution was selected. The age range with the highest confidence interval was marked in bold and selected as the calibrated CE (cal CE) range of the sample for obtaining **single calendar age values**, expressed in calendar years. The mean value of the selected age range was calculated. The sample ages represent the difference between the year 2020 (or the year of stem/baobab demise) and the mean value of the selected range, with the corresponding error. Sample ages and the corresponding errors were rounded to the nearest 5 years.

For the baobab Chapman baobab, **the stable carbon isotope analysis** was performed for paleoclimate reconstruction.

For **sample/segment prepartion and pretreatment,** wood samples were cut into segments so as to correspond (as much as possible) to a growth ring.

Segment pretreatment included Soxhlet extractions and the α-celullose extraction method of Loader et al. (1997). Aliquots of 5-6 x 10^{-5} g were subjected to the analysis of the $^{13}C/^{12}C$ ratio, namely $\delta^{13}C$.

Chapter III. Features of the *Adansonia* genus
(exemplified and explained by the investigation of the Warang baobab)

1. Multiple stems

The baobab with the largest circumference ever recorded for the northern hemisphere is located in Warang, Thiès region, Senegal (Patrut A. et al., 2017a).


Figure 2. The baobab of Warang, Senegal, consists of 18 partially fused stems.

The baobab of Warang, which can be found at 14º22.250' N, 016º56.330' W, has the following measurements: h = 22,1 m, cbh = 28,69 m and V = 250 m³. This baobab consists of no less than 18 stems, which is a record for the *Adansonia* genus (Fig. 2).

The original methodology of Patrut (Patrut A. et al., 2006a, 2006b, 2007, 2010a), allowed for the identification of the multiple stems phenomenon in baobabs with seemingly unique stem. This feature allows for baobabs to reach one of the most stable architectures of the genus (Patrut A. et al., 2018; 2016a; 2015c; 2015b; Patrut R.T., 2015).

Research shows that all baobabs with a circumference ≥ 14 m have multiple stems. This is owed by the unusual ability of baobabs to generate new stems periodically. These new stems may fuse in time among themselves or with other, older stems, leading to increasingly complex architecture. Thus, the only possibility of investigating such structures is by radiocarbon dating.

2. False stems

The baobab of Warang has a bell-shaped cavity delimited by three stems plus two additional stems on either side of the cavity entrance. Two wood samples were collected from the cavity walls (3 dated segments, labelled 1a, 1b and 2a) and 2 other samples from a false stem (2 dated segments, labelled TF-1 și TF-2). TF-1 originates from the base of the false stem, close to the fusion line with other stems, while TF-2 originates from the middle of the false stem, as depicted in figure 3).

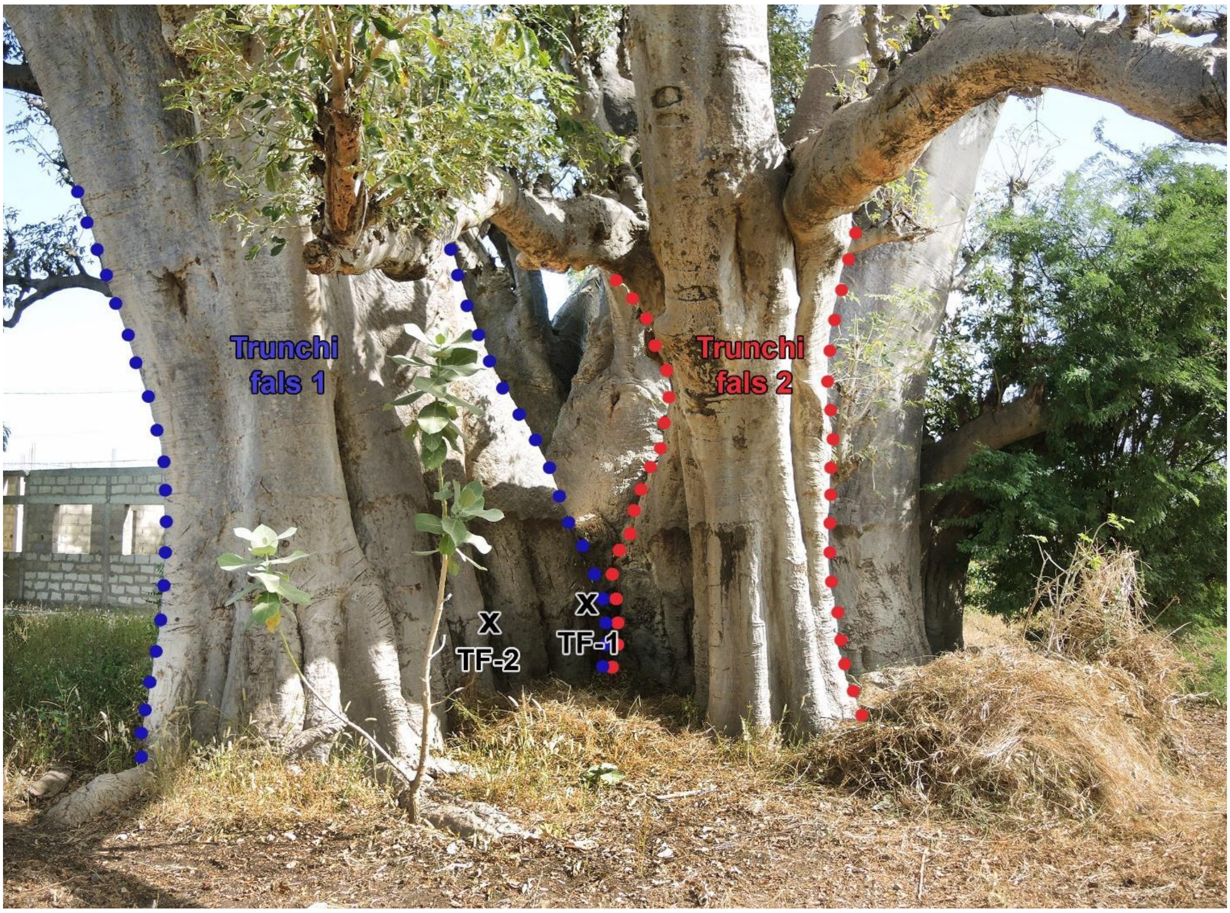

Figure 3. The 2 false stems of the baobab of Warang are disposed in a V shape. The false stems (Trunchiul fals 1 and Trunchiul fals 2) are highlighted with blue and red dots. The sampling points TF-1 and TF-2 are marked with an „X”.

The radiocarbon dates of the samples from the false stem are 262 ± 22 and 157 ± 24 BP, which translates to calibrated ages of 370 ± 15 (TF-1) and 265 ± 25 (TF-2) years. The results clearly show that the oldest age is located toward the upper contact with the larger adjacent stem, while the age values decrease toward the opposite sharp extremity (Fig. 4).

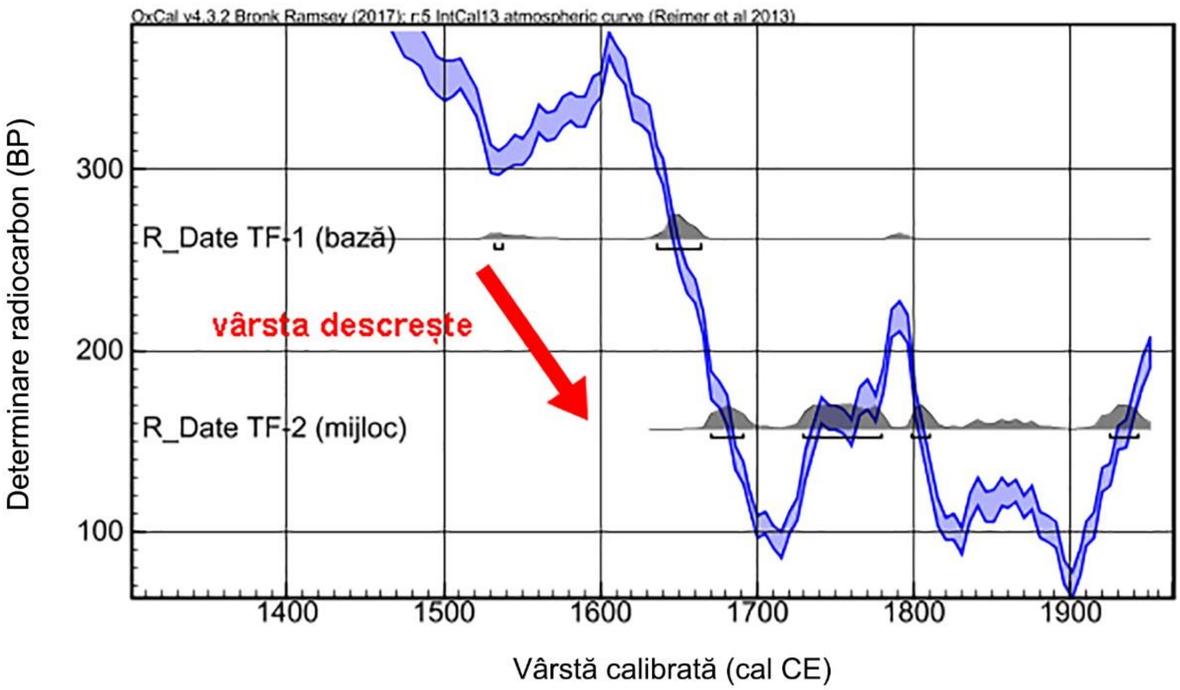

Figure 4. The radiocarbon ages and calibrated age ranges of the samples TF-1 and TF-2 on the IntCal13 calibration curve. The red arrow evinces the age value decrease of a false stem from the fusion line to the opposite sharp extremity.

Radiocarbon dating of the Warang demonstrated the occurrence of false stems, which have a trapezoid or triangular shape in horizontal section. Such features were named LTSB (long triangular stem buttress) and act as an anchor. False stems emerge from a large stem and extend upward obliquely by branching out, while the lower part gradually merges with the radicular system.

For the baobab of Warang, which grows on sandy soil, 6 of the 18 stems are false ones (Patrut A. et al., 2017a).

3. Types of architecture for baobabs with multiple stems: Ring-shaped structures and false cavities

The ring-shaped structure is the most common type of architecture for monumental baobabs and was discovered by radiocarbon dating (Patrut A. et al., 2015a; 2016b). As the name suggests, the stems are disposed in a more or less circular manner, similar to a ring. Ring-shaped structures are a consequence of the multiple stems phenomenon. There are 2 major types of ring-shaped structure, i.e. open and closed.

3.1 Closed ring-shaped structure

All ring-shaped structures have at least one false cavity inside. Thus, the (almost) perfect fused multiple stems grow around an empty space, called false cavity. This space was never filled with wood because the stems grew around it in time (Fig. 5).

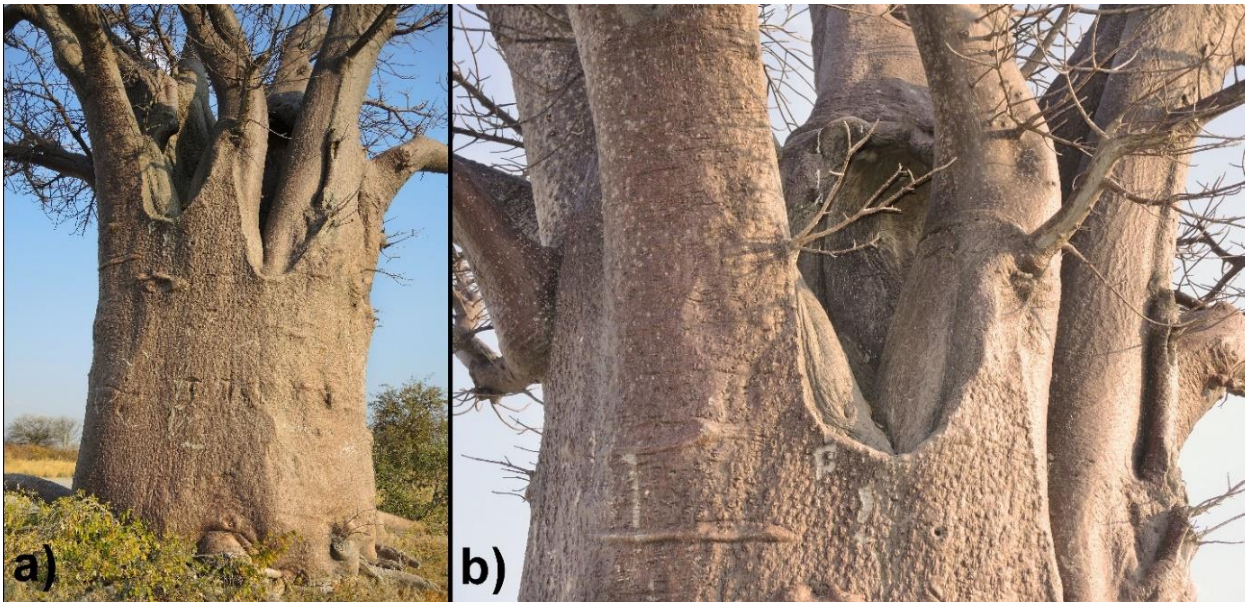

Figure 5. Image (a) depicts a baobab with an open ring-shaped structure. The almost perfectly fused stems enclose a false cavity. The cavity is still accessible and does not have a ceiling yet. Image (b) shows the primary branches in great detail. The cavity walls are covered by bark.

The baobab of Warang has a closed ring-shaped structure with a false cavity, defined by 3 fused stems (Patrut A. et al., 2017a). Two samples corresponding to different stems were collected from the cavity walls. Two segments were investigated by radiocarbon from the longest sample 1 (1a at 0,18 m and 1b at 0,40 m depth in the wood from the sampling point). Only the deepest end of sample 2 was dated (2a at 0,36 m). Radiocarbon dating results are presented in figure 6.

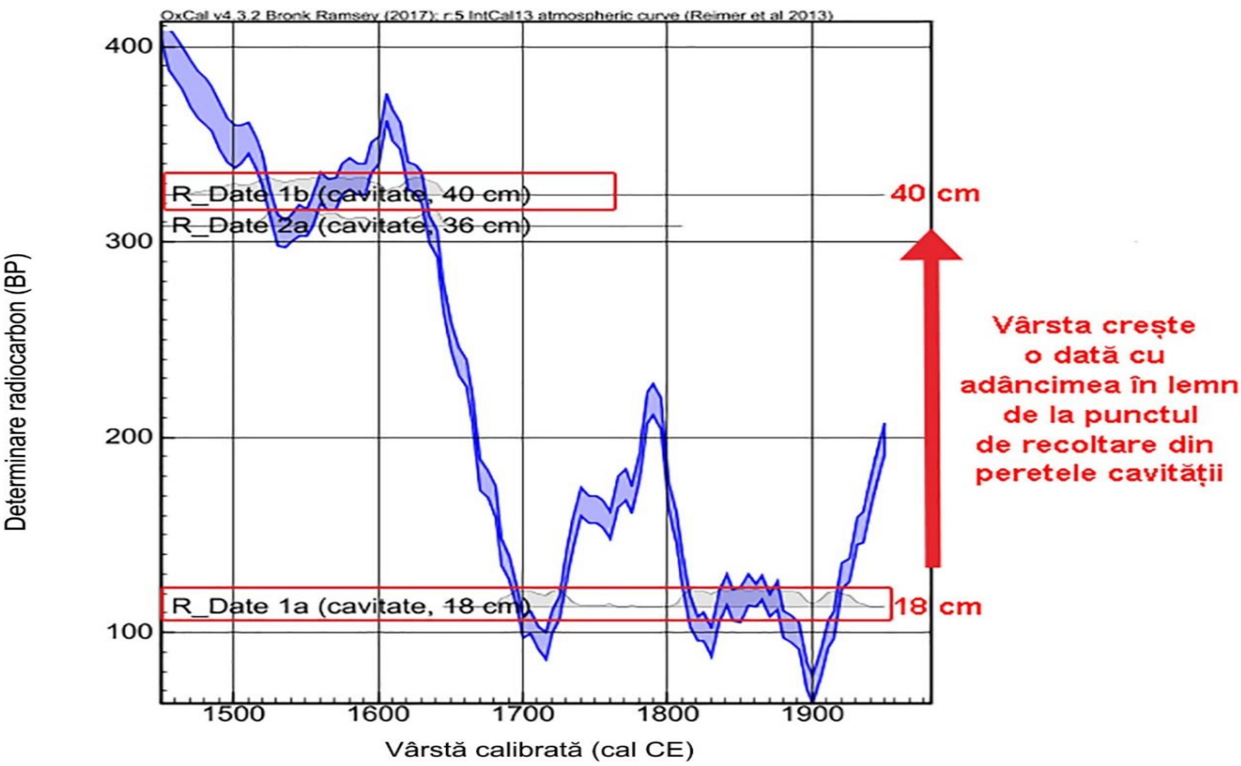

Figure 6. The radiocarbon results of samples 1 and 2 shown on the IntCal13 calibration curve. The red arrow indicated that the age increases with the depth into the wood from the sampling point in the false cavity walls.

The stems that build the false cavity are always the oldest of the baobab (Patrut A. et al., 2017c; 2017e). For samples collected from a false cavity, the age sequence increases with the depth into the wood up to a point/area of maximum age, then it decreases toward the exterior of the tree. The oldest part of the fused stems is located between the false cavity walls and the outer part of each stem, always closer to the cavity. Sample 1 exhibits this typical age sequence yet it was too short to reach the point/area of maximum age. The maximum age of the baobab of Warang is 500 ± 50 years.

3.2. Open ring-shaped structure

Baobabs with an open ring-shaped structure do not have a false cavity. The individual stems can be easily recognised, are fused only at the base and are also leaning at various degrees (Fig. 7). Ring-shaped structures are mandatory for baobabs to reach old ages and remarkable sizes.

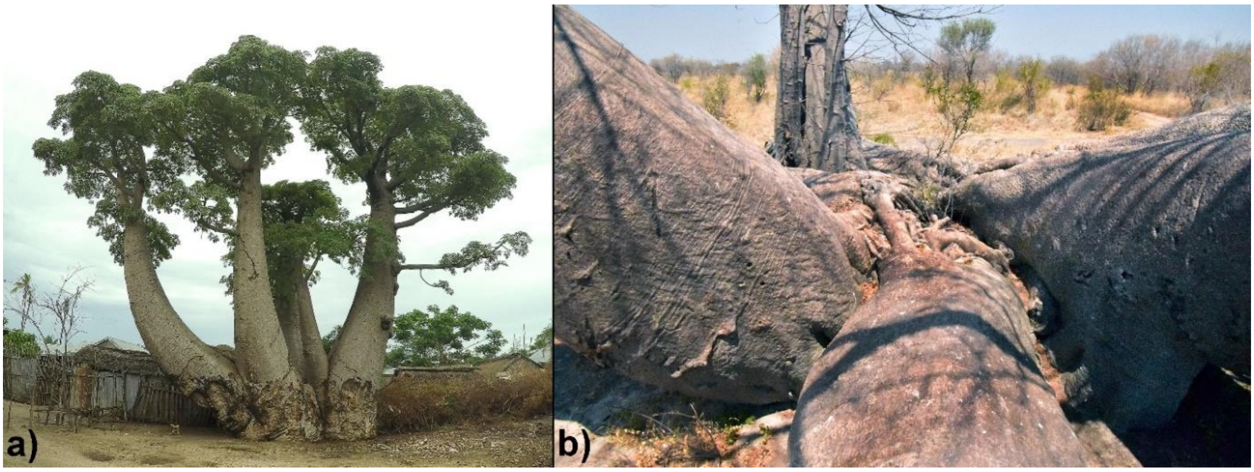

Figure 7. An *A. grandidieri* from Bemanonga exhibits an open ring-shaped structure. The stems, which belong to several generations, can be clearly identified as they are fused only at the base (a). Image (b) shows an *A. digitata* from Namibia with an open ring-shaped structure; the stems have a strong lean and are knitted at the base.

The main trait of false cavities are bark-covered walls. A baobab with multiple stems can be included in the following categories: cluster structure (Patrut A. et al., 2010c; 2015c; 2020), closed ring-shaped structure with false cavity (Patrut A. et al., 2015a; Patrut A. et al., 2017a), double closed ring-shaped structure with 2 interconnected false cavities (Patrut A. et al., 2015d), double closed ring-shaped structure with 2 separate false cavities (Patrut A. et al., 2016c), triple closed ring-shaped structure with 3 interconnected false cavities or open ring-shaped structure with no cavity (Patrut A. et al., 2017c; Patrut A. et al., 2019b). Other architecture types were identified such as the mixed ring-shaped structure or the incomplete ring-shaped structure. Some structures can have additional stems outside the ring (Patrut R.T., 2013; Patrut R.T., 2015).

Chapter IV. The growth stop phenomenon

Radiocarbon dating allowed for the discovery of unique architectures (Patrut A. et al., 2015a; 2015d; 2016c; 2018; 2020). The presence, absence and irregular character of baobab growth rings suggest a remarkable adaptation and the deviation from well-established conventions. Sometimes, growth rings closest to the bark are very old instead of being very young. Here we presented the experimental results obtained for several *Adansonia* specimens, which exhibit an unexpected phenomenon.

1. Baobabs and their location. Several baobabs belonging to the *A. digitata*, *A. grandidieri* and *A. rubrostipa* species were investigated and AMS radiocarbon dated.

The Pafuri Outpost baobab was located in the Kruger National Park, Limpopo province, South Africa, at 22°26.647'S, 031°04.745'E. The Pafuri Outpost baobab, which collapsed in 2008, had the following dimensions: h = 18 m, cbh = 14,20 m and V = 60 m^3. This baobab is the record holder for the largest circumference ever identified for a single-stemmed baobab.

The historic baobab Dorslandboom can be found south of Khaudum National Park, Otjozondjupa region, Namibia (Fig. 8). Its GPS coordinates are 19º18.061'S, 020º39.636'E. Dorslandboom has the dimensions: h = 14,3 m, cbh > 25 m and V = ca. 150 m^3. The baobab exhibits an open ring-shaped structure, with 8 large, nearly collapsed stems, some fractured, other with new shoots and stems. The largest stem, which in fact consists of 2 fused stems, was radiocarbon dated after its collapse in 2006. In the meantime, it decayed and disappeared.

Figure 8. The African baobab Dorslandboom has an open ring-shaped structure comprised of old toppled and young standing stems. This appearance resembles the kraken (a).

The historic baobab Leydsdorp near Gravelotte, Mpumalanga region, South Africa has the dimensions: h = 21,0 m, cbh = 19,20 m and V = 230 m^3. Its GPS coordinates are 23º57.427' S, 030º34.509' E. The baobab has a closed ring-shaped structure consisting of 5 stems and an accessible false cavity.

The Gouye Ndiouly baobab is located in Kahone, Kaolack region, Senegal, at 14º09.372′ N, 016º01.644′ W. Gouye Ndiouly experienced a total collapse in the past. From the surviving remains 5 new stems emerged. Only one of the original stems remained. At present, the baobab has the following dimensions: h = 16,0 m, cbh = 14,40 m and V = 80 m^3.

The Lebombo baobab (Lebombo Eco trail baobab) can be found in the Limpopo National Park, Mozambique, at 23º15.765' S 031º33.309' E. It has the dimensions: h = 18,5 m, cbh = 21,44 m and V = 220 m^3. The Lebombo baobab has a closed ring-shaped structure of 5 fused stems (Fig. 9). A sixth relict stem was identified only by some remains (Patrut A. et al., 2015a).

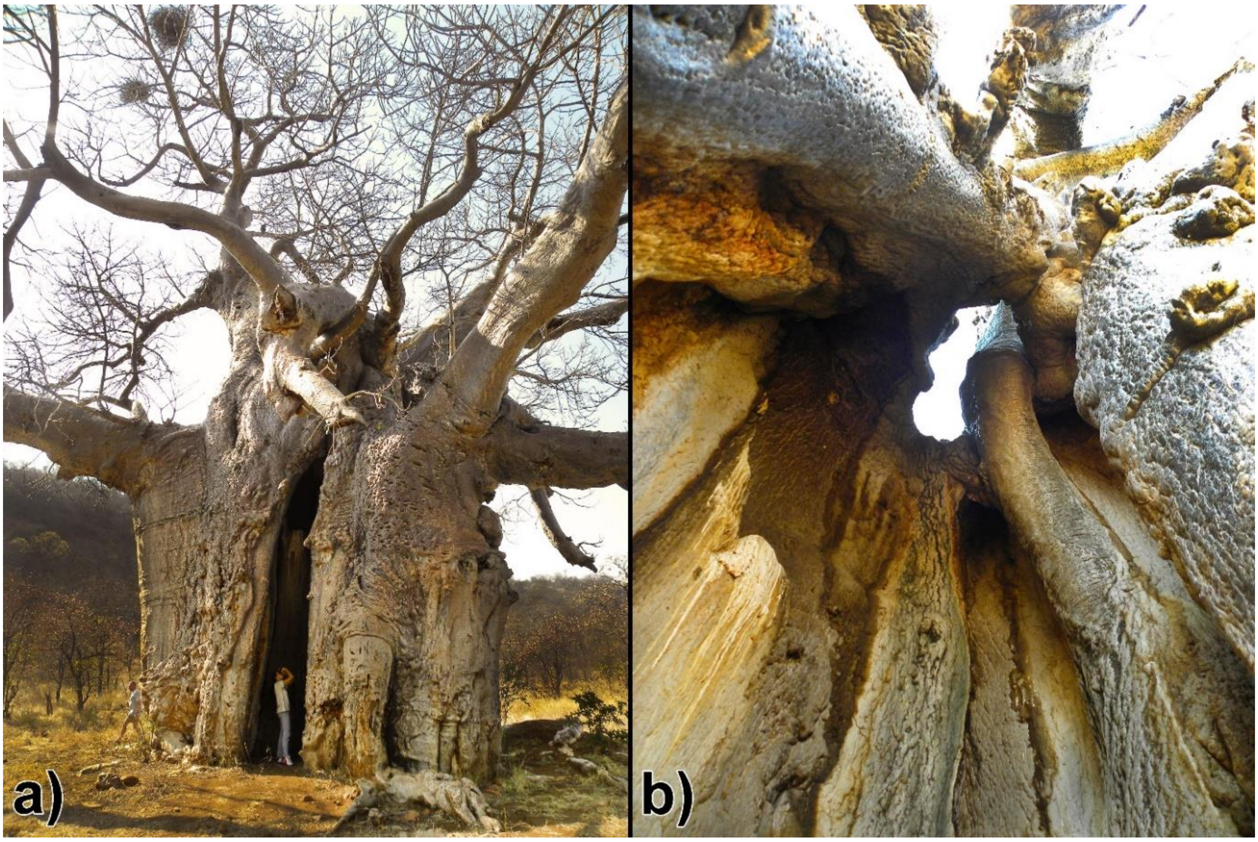

Figure 9. The closed ring-shaped structure was discovered after the radiocarbon investigation of Lebombo baobab (a). The ceiling of the cavity is shown; the cavity walls clearly look like stems (b).

The Grand-mère baobab or Grandmother, which belongs to the *A. rubrostipa* species, is one of the best-known baobabs of Madagascar. The baobab is located in the Tsimanampetsotsa National Park, at 24º02.707' S, 043º45.266' E (Patrut A. et al., 2015c; Patrut R.T., 2015). The following measurements were recorded: h = 7,47 m, cbh = 9,67 m and V = 25 m^3. The baobab consists of 3 perfectly fused stems fuzionate.

The Tsitakakoike baobab of the *A. grandidieri* species was located in the Andombiro forest, Morombe area, Madagascar, at 21º33.9770' S, 043º30.0280' E (Patrut A. et al., 2015b). Due to climate changes, after 3 years of protracted drought followed by the intense floods of the Ava cyclone in 2018, Tsitakakoike started to collapse (Fig. 10). This sacred monumental baobab had the dimensions: h = 14,6 m, cbh = 27,36 m and V = 520 m^3. Tsitakakoike had a closed ring-shaped structure consisting of 5-6 stems perfectly fused around a false cavity. The partial collapse allowed access to the false cavity, which had a volume of ca. 175 m^3.

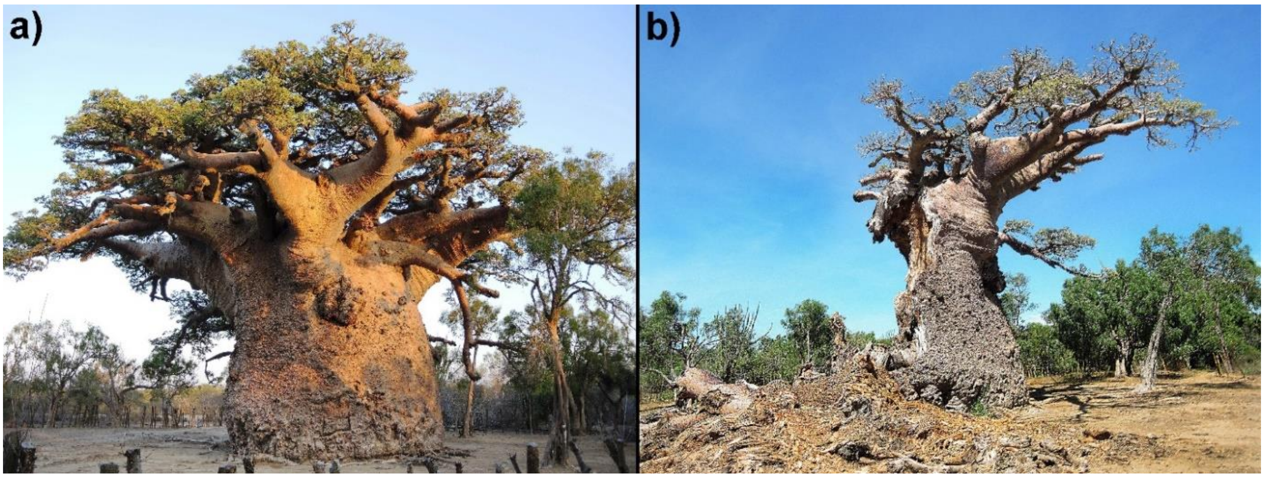

Figure 10. The gigantic Tsitakakoike was one of the largest baobabs alive (a). Today, the baobab is in an advance state of decay caused by the partial stem collapse in 2018 (b).

2. Sample collection. For the Pafuri Outpost baobab, a complete wood section was obtained, with no missing parts. Several growth rings were investigated by radiocarbon. For the other 7 baobab, multiple wood samples were collected with an increment corer and subsequently dated.

3. Results interpretation.

Pafuri Outpost. The section obtained from the Pafuri Outpost baobab enabled a thorough growth ring count and an additional radiocarbon age determination of selected growth rings. Thus, for growth ring 490, which is the pith of the tree, the radiocarbon age was found to be 1000 ± 20 BP. This value corresponds to a calibrated age of 895 ± 25 years. For growth ring 40, the radiocarbon age of 412 ± 20 BP corresponds to a calibrated age of 530 ± 20 years. Results show that the baobab exhibits subannual rings and completely stopped its radial growth around 1500 CE. Pafuri Outpost continued to flush leaves, develop flowers and pods normally, until the year of its collapse. The period during which growth stop was triggered concurs with the Little Ice Age (LIA) (Tyson et al., 2000; Woodborne et al., 2016). It is likely that the baobab stopped growing due to harsh environmental conditions triggered by climate factors.

Dorslandboom. The open ring-shaped structure enabled this baobab to survive after the 2006 collapse. The dating of segment D11-a showed that the rings closest to the bark have an age of 1370 ± 15 years. Thus, the double stem from which it originates, stopped its radial growth 640 years ago. The age of this double stem was reported to be 2100 years (Patrut A. et al., 2018). Consequently, growth stop can be triggered by very old age.

Leydsdorp and Lebombo. A third factor, which can determine growth stop is the tendency to maintain a stable (internal) architecture. The samples originating from the Leydsdorp baobab show that the stems stopped growing only towards the false cavity at different points in time, namely 260 (toward the east) and 160 years ago(toward the west). Thus, the oldest part of the stem is always located closer to the cavity walls than to the exterior of the tree.

The Leydsdorp case demonstrates that the stems stopped growing towards the cavity 155-255 years ago, after reaching a stable architecture that compensates the significant lean of the baobab (about 20-30° to the west). Without the growth stop phenomenon, the baobab probably would have collapsed due to the generated instability.

Wood samples from the cavity walls and the outer part of Lebombo baobab were extracted. According to dating results, all 5 stems of the baobab (Patrut A. et al., 2015a) stopped growing towards the cavity but continued to expand along the outer circumference at a quasi-constant rate for another 300 years. The growth stop phenomenon of stems towards the cavity was caused by a stable internal architecture of high symmetry.

Gouye Ndiouly. A fourth factor that may trigger growth stop was found to be a major trauma experienced by the baobab in the past, such as fire or a collapse. The surviving stem(s) can stop their growth completely. The case of Gouye Ndiouly baobab proves this. The last remaining original stem was radiocarbon dated. Sample segment GN-1a, which consists of the outermost rings, has a calibrated age of 170 ± 40 years. By this value, the baobab collapsed around the year 1850 CE.

Grand-mère and Tsitakakoike. The growth stop phenomenon is not limited to the African baobab (*A. digitata*). The oldest dated specimens of the *A. rubrostipa* and *A. grandidieri* species, namely Grand-mère and Tsitakakoike, exhibit the growth stop phenomenon for their oldest stems.

Results demonstrate that baobabs affected by the growth stop phenomenon can survive in this state for centuries while seeming to function normally by flushing leaves, generating flowers and pods. The ability of baobabs to store a large water amount in their trunk may enable specimens of the *Adansonia* genus to survive in a good physiological state even after the onset of the growth stop phenomenon.

Chapter V. Records

1. Superlative baobabs of Savé Valley: Searching for the oldest living baobab

Savé Valley Conservancy, which is located in Zimbabwe comprises several properties (ranches) (Lindsay et al., 2009). In this reserve, thousands of African baobabs are found, out of which 4 specimens have monumental sizes (cbh > 23 m) and ages exceeding 1000 years. These baobabs were investigated by radiocarbon.

1.1. Baobabs and their location

Matendere baobab. This tree (Fig. 11) is located on the Matendere ranch, at 20º00.325' S, 032º03.808'. The following measurements were recorded: h = 22,5 m, cbh = 26,30 m and V = 300 m^3. The baobab consists of a closed ring-shaped structure defined by 5 fused stems but also has 2 additional stems outside the ring (Patrut A. et al., 2019a).

Figure 11. The location of Matendere baobab is difficult to reach due to the overgrowth.

Chishakwe baobab. The Chishakwe baobab is located on the Chishakwe ranch at 20º06.656' S, 032º04.991' E. The following measurements were recorded: h = 26,1 m, cbh = 26,56 m, V = ca. 375 m^3. The baobab has a total of 7 stems, out of which 5-6 define a closed ring-shaped structure with a false cavity inside. Our research shows that this baobab is the tallest and largest Zimbabwe in terms of volume (Fig. 12) (Patrut A. et al., 2019a).

Figure 12. The Chishakwe baobab is the tallest of Zimbabwe (a). The farm owners placed rocks at the base of the tree to prevent elephant damage (b).

Mokore bobab. This massive baobab is located on the Mokore ranch at 20º23.950' S, 036º06.836' E. It is the most famous baobab of Savé Valley (Fig. 13). The following measurements were recorded: h = 23,2 m, cbh = 28,11 m și V = ca. 320 m^3. The trunk consists of 8 stems, out of which one is a false stem that acts as an anchor. Supports are recommended to prevent the false stem from collapsing as it is fractured. Our investigation shows that this baobab has the biggest circumference for Zimbabwe (Patrut A. et al., 2019a).


Figure 13. Mokore baobab has the biggest recorded circumference for Zimbabwe, namely cbh = 28,11 m.

Humani Bedford baobab. The Humani Bedford baobab can be found in Bedford Block, a part of Humani ranch (Patrut A. et al., 2019a). The baobab is located at 20º24.474' S, 032º14.135' E.

Humabi Bedford exhibits a closed ring-shaped structure comprising 3 fused stems that partially define a false cavity (Fig. 14). A relict stem still exists and it used to close the false cavity completely. The following measurements were recorded for this baobab: h = 18,2 m, cbh = 23,65 m, V = 240 m^3.

Figure 14. View of the Humani baobab and its false cavity. The fused stems are marked by I, II and III, white the relict stem IV cannot be seen.

1.2. Sample collection. Several samples were collected out of the outer parts of the 2 superlative baobabs Matendere, Chishakwe and Mokore. For the Humani baobab, 2 samples were extracted from the cavity walls (HB-1 and HB-2) and one from the opposite outer part of HB-1 (HB-11). All 3 samples originate from stem I. Several segments were selected to undergo AMS radiocarbon investigation.

1.3. AMS results and calibrated ages. The results for the Matendere, Chishakwe and Mokore baobabs are shown in Figure 15. The results for the Humani Bedford baobab are presented in Figure 16.

The 2 oldest segments were reported for the Matendere baobab. Thus, samples MAT-1 and MAT-2 have a radiocarbon age of 1529 ± 14 and 1305 ± 19 BP, which translate to calibrated ages of 1430 ± 15 and 1310 ± 25 calendar years (Fig. 15).

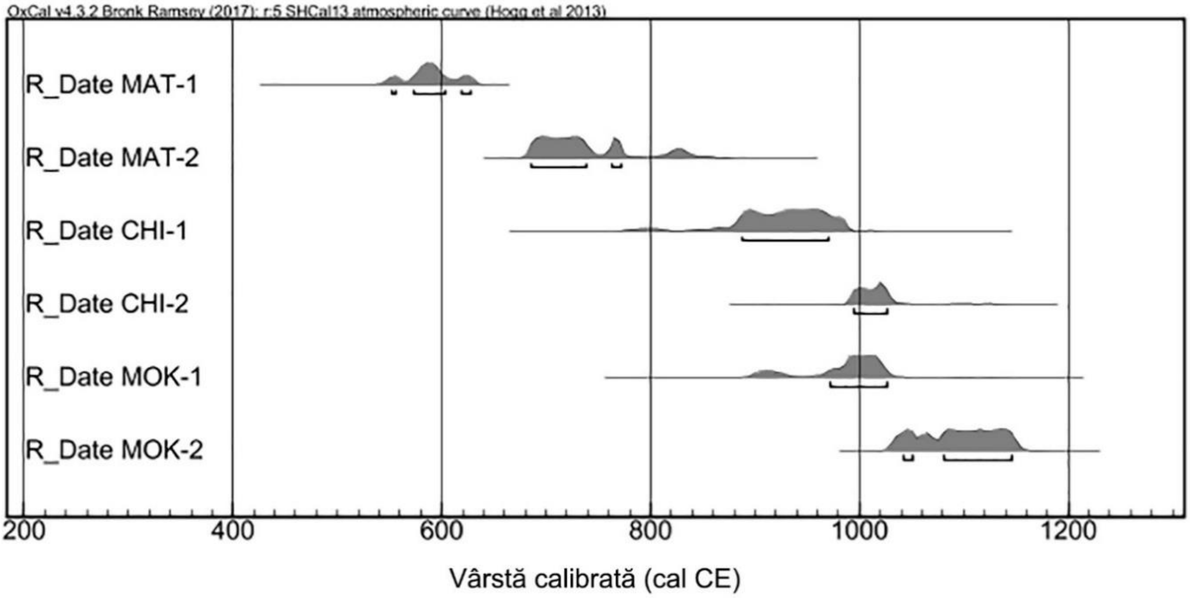

Figure 15. The calibrated ages demonstrate that Matendere is the oldest specimen out of the 3 investigated superlative baobabs, while Mokore is the youngest.

The Matendere, Chishakwe and Mokore baobabs have the same type of architecture, namely closed ring-shaped structure with false cavity inside. Some additional stems can be found outside the ring as well. The extrapolate ages of these 3 monumental baobabs of Savé Valley are as follows: 1550 ± 100 for Matendere and 1200 ± 100 years for Chishakwe and Mokore respectively.

1.4. The architecture of the Humani Bedford baobab. For Humani Bedford the age values of samples increase with the depth into the wood from the sampling point. This result confirms the architecture type of this baobab, i.e. closed ring-shaped structure. Photo and video material also show that the baobab is composed of 3 perfectly fused stems, each with a distinct canopy.

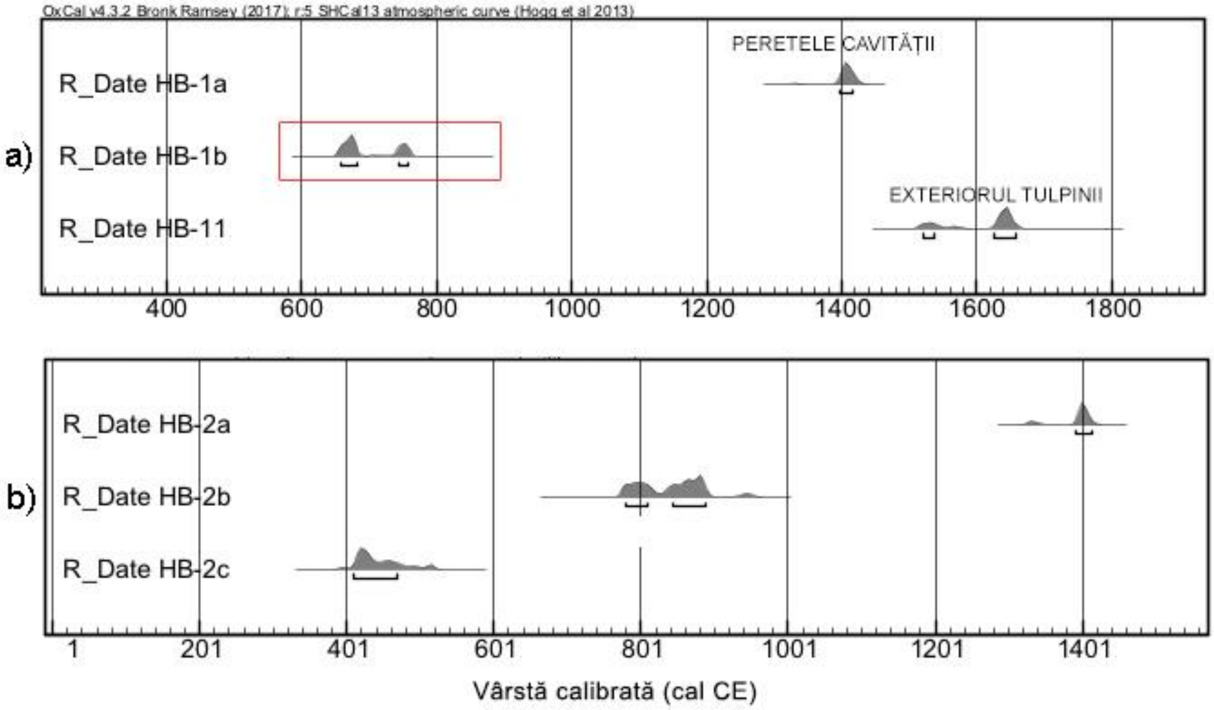

Figure 16. Calibrated ages of the HB-1 and HB-11 samples exhibit the typical age sequence for baobabs with a closed ring-shaped structure. Segment HB-1b, which is highlighted with a red border, is older than HB-1a and HB-11 (a). The sequence of calibrated ages for the longest and oldest sample of the Humani Bedford baobab is shown (b).

1.5. The age of Humani Bedford baobab. The maximum age of stem I is greater than the age value for segment HB-2c (1580 ± 30 years), which originates from a 0,25 m depth. The distance between segment HB-2c and the exterior of the trunk is 0,95 m. According to experimental results, the area of maximum age is located about 0,35 – 0,40 m from the cavity walls and about 0,85 – 0,80 m from the outer part of stem I. Thus, by calculating growth rates, the extrapolated age of the oldest stem of the Humani Bedford baobab is 1800 ± 100 years. Consequently, the Humani Bedford baobab becomes the oldest living African baobab and angiosperm, with accurate dating results.

2. Searching for the largest baobab: The Grandidier baobab of Isosa

Until 2018, the monumental baobab Tsitakakoike was considered the largest *A. grandidieri* specimen with a total volume of 520 m^3 and an age of 1400 ± 100 years (Patrut A. et al., 2015b).

The investigation results of the currently largest baobab and angiosperm of the world (in terms of volume) are presented. This superlative baobab is the Grand Reniala of Isosa.

2.1. The baobab and its location. The baobab can be found in the Morombe area, at 21º37.976' S, 043º34.474' E. For the baobab of Isosa has the following measurements: h = 21,6 m and cbh = 23,22 m. The circumference at the base is 24.20 m and decreases to 21 m at the height of 12 m. Thus, the columnar trunk is almost cylindrical, up to the height of 12.2 and 14.5 m, where it forks into several large branches with diametres up to 2 m. The horizontal dimensions of the impressive canopy are 45.2 (north-south direction) and 37.2 m (west-east).

The calculated volume of the trunk is 485 m^3 to which the canopy volume of 55 m^3 is added, to result in a total wood volume of 540 m^3. This value is the highest ever recorded for a specimen of the *Adansonia* genus (Fig. 17) Thus, Grand Reniala of Isosa is the largest baobab and angiosperm in the world, in terms of volume.

2.2. Sample collection. For determining the age by radiocarbon dating, 3 samples were collected (1, 2 and 3) out of different stems. Three segments were dated from each sample (a, b, c).

2.3. Architecture and age of the Grand Reniala baobab. The results of the radiocarbon investigation of the Grand Reniala of Isosa show that is has a cluster structure composed out of 5 perfectly fused stems. For the Grandidier baobab of Isosa, the values of the calibrated age sequence becomes higher with the depth into the wood for all 3 samples that were analysed. Results also showed that all 5 stem of the baobab have similar ages and belong to the same generation. By calculating growth rates, the age of the baobab was established.

In a conservative estimate, the Big Reniala of Isosa is at least 1000 ± 100 years old.

Figure 17. Grand Reniala is almost cylindrical up to the main branches. This specimen is the largest angiosperm in terms of volume in the world.

Chapter VI. The Chapman baobab: historical and scientific aspects

1. Radiocarbon investigation

The most famous of historic baobabs is undoubtedly the Chapman baobab, located on Missionary Road of Makgadikgadi Pans, Central district, Botswana. On the 7th of January 2016, the monumental Chapman baobab suddenly collapsed (Fig. 18). Research on the age, development and architecture of the African baobab Chapman are presented and the factors which contributed to the collapse of this living natural monument are analysed.

1.1. The baobab and its location. The GPS coordinates of the location of Chapman are 20º29.404'S, 025º14.971'E (Patrut A. et al., 2019).

Figure 18. The dramatic image shows the large broken stems and branches of the famous Chapman baobab.

The area has a semi-arid climate (Grey and Cooke, 1977). The only available water source for the baobab was rainfall. Thus, the wood of Chapman baobab responded to rainfall availability by forming growth rings. By this the the climate signal was transfered and recorded into the chemical parameters of the growth ring.

The following measurements were recorded for the Chapman baobab: h = 22,6 m, cbh = 25,90 m, V = 275 m^3. The architecture consists of an open ring-shaped structure composed of 6 main stems (from I to VI) of different sizes, fused at the base (Fig. 19). The stems were fused up to a height of 2,0-2,2 m and built a west-east-oriented accessible platform.

The Chapman baobab also had a natural cavity that was located in 3 stems (I, II and III). This cavity was used as a post office in the 19th century (Pakenham, 2004).

Figure 19. The Chapman baobab has an open ring-shaped structure defined by 6 stems that seem knitted at the base. The stems are numbered I to VI.

1.2. Sample collection. Several wood samples were extracted by increment corers before and after the collapse from stems I, II, III, IV and VI (labelled CH-1, CH-2, CH-3, CH-4 and CH-6). The deepest end (closest to the pith) of each stem was radiocarbon dated to ascertain stem ages. Out of samples CH-1 and CH-4 the outer part of the sample (closest to the sampling point) was also investigated.

1.3. Determining the water content. The water content of samples was determined prior and after the collapse.

1.4. AMS results and calibrated ages. Radiocarbon ages and corresponding calibrated age ranges of segments originating from the Chapman baobab are presentet in table 1.

Table 1. Rezultatele datării cu radiocarbon and vârste calibrate ale segmentelor ce provin din baobab Chapman.

Sample/segment code (stem)	Depth[1] (10^{-2} m)	Radiocarbon date [error] (^{14}C year BP) or *fraction modern	Cal CE range 1σ [confidence intrval]	Sample age in 2016 [error] (calendar years)
CH-1a (I)	0,5	1,4676 [±0,0047]*	**1972-1973 [68,2%]**	43-44 [± 0]

CH-1x (I)	0,75	618 [±18]	1326-1341 [28,9%] **1390-1404 [39,3%]**	620 [±5]
CH-2x (II)	0,70	353 [±25]	**1508-1584 [61,4%]** 1620-1628 [6,8%]	470 [±40]
CH-3x (III)	1,90	1381 [±22]	**654-681 [63,0%]** 749-752 [5,2%]	1350 [±15]
CH-4a (IV)	0,5	1,0173 [±0,0036]*	**1956-1957 [68,2%]**	59-60 [±0]
CH-4x (IV)	0,78	340 [±24]	**1510-1576 [56,0%]** 1622-1636 [12,2%]	470 [±35]
CH-6x (VI)	1,25	745 [±18]	**1278-1300 [68,2%]**	725 [± 10]

[1]Depth in wood from the sampling point.

1.5. The age of stems. The segments marked with an x, which represent the fragments closest to the pith, are also the oldest. The stem ages were calculated by extrapolating the distance from the position of the segments to the pith of the corresponding stem. The results show that the main stems of Chapman baobab belong to 3 generations: 1350-1400 years (stem III), 800-1000 years (stems I, V and VI) and 500-600 years (stems II and IV).

1.6. Architecture of the Chapman baobab. Open ring-shaped structures usually consist of 5-8 stemuri partially fused stems (at the base). In time, some stems may collapse and disappear while new stems may emerge to complete the ring. In the case of Chapman baobab, only stem III belongs to the original ring.

1.7. The collapse of Chapman baobab. On January 7, 2016, 7 o'clock, all stems of the Chapman baobab simultaneously collapsed (Fig. 18). Old trees that are close to the end of their life cycle do not suddenly collapse, but start breaking off over a longer period that lasts for month or even years. The fact that all of Chapman's stems collapsed unexpectedly was an exceptional event, a consequence of a complex interaction of four main factors:

i) the critical dimension of the natural cavity („postbox cavity"). The natural cavity was created by a fire originating in stem II and progressively extended into 3 stems (II, III and I), by a continuous decay process.

ii) the low water content of stems asociated with extreme drought. Studies on water content of baobab wood indicate a high value of up to 79% (Chapotin et al., 2006c). Thus, large baobabs are standing upright due to a hydrostatic pressure and a gravitational effect. The investigated water content of 2 stems was 9-10% lower after the collapse, reaching the values of 39,8 and 43,1%. Usually, the first rainfall occur in September. Nevertheless, the rainy season of 2015-2016 started in February. The El Niño episode of 2015-2016 was one of the most intene ever recorded, similar to the dramatic episodes of 1982-1983 and 1997-1998, which had severe negative impact all over the world (Zhai et al., 2016; L'Heureux et al., 2017). The devastating droughts, which also affected

Botswana during that period had a significant contribution to the collapse of the Chapman baobab (Fig. 20).

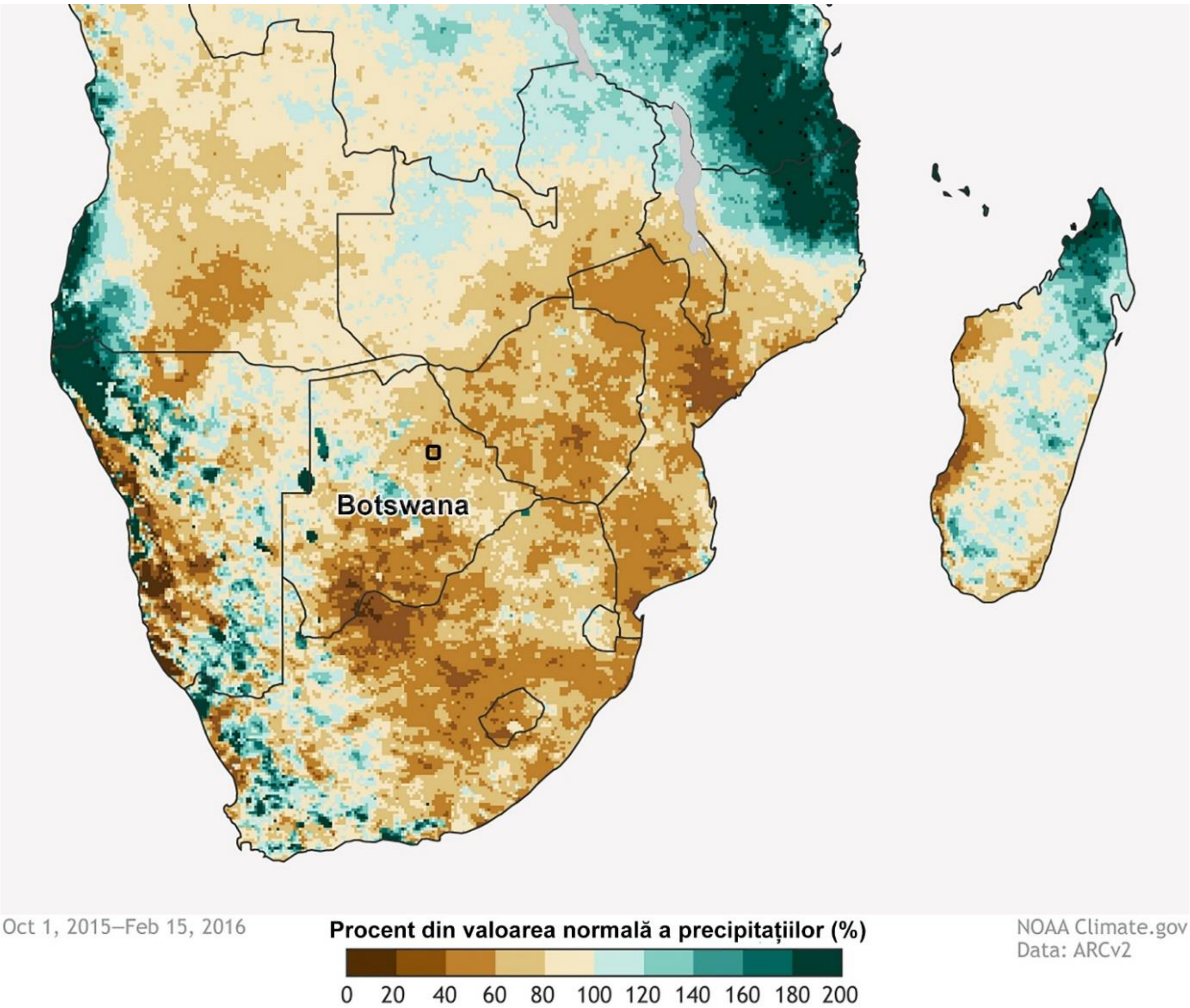

Figure 20. During October 2015 - February 2016, the rainfall level of southern Africa was profoundly influenced by the intense El Niño event. The area of the Chapman baobab of Botswana, which is indicated by a black square, was severely affected by drought; (adapted from NOAA Climate.gov).

iii) the lean of the stems. The stems of Chapman baobab had various leaning degrees, which increased by approximately 5° during the last 50 years, contributing to the fracturing of the platform.

iv) the old age of the tree. According to radiocarbon dating, the Chapman baobab is the 11th oldest African baobab (see Chapter VII). In 2018, Patrut A. et al. reported the demises of the largest and oldest baobabs of (mainland) southern Africa, amongst which was also the Chapman baobab.

2. Climate change in southern Africa

(Semi)arid tropical areas are considered the most exposed to climate changes, showing a high climatological risk of desertification (Spinoni et al., 2015). In this context, southern Africa is particularly vulnerable (IPCC, 2014). For this region, there is still a high degree of uncertainty regarding precipitation regimes due to a severe lack of long-term instrumental records (Trouet et al., 2010, Engelbrecht et al., 2015, Gebrekirstos et al., 2014, Slotta et al., 2017, Kusangaya et al., 2014). Thus, paleoclimate reconstructions are a solid alternative for creating and validating hydrological climate models. The use of tree growth rings as a proxy is a promising tool, yet few tropical species fulfill the requirements for traditional dendrochronological recontructions (Détienne, 1989; Gebrekirstos et al., 2014).

A modern method for obtaining dendroclimatological chronologies is by the stable isotope analyses of tree growth rings combined with radiocarbon dating especially for trees with anomalous growth ring sequence. Robertson et al. (2006) demonstrated the potential use of the African baobab as a climate proxy, showing that its growth episodes are positively correlated with rainfall. Accordingly, the baobab is a rainfall proxy for the corresponding area.

The interannual variability of rainfall is associated with sea suface temperatures (SST) in the Agulhas Current Core region, which influences the east-west movement of tropical temperate troughs (TTTs). Fauchereau et al., (2009) proved that the El Niño has a complex, often indirect, influence on southern Africa.

Research that focuses on climate change and precipitation variability over the last 30 years were unable to pinpoint a clear tendency for southern Africa, yet all studies agree with an increase of the duration and intensity of the dry season (Kusangaya et al., 2014; Mphale et al., 2014).

For evaluating the resilience of the society in Botswana to increased rainfall heterogeneity, the impact of past droughts must be analysed.

Thus, any new climate archive is an important contribution for identifying forcing mechanisms, for projecting and validating realistic scenarios and for understanding the wet-dry successions. Woodborne et al., (2015, 2016) attributed the dry conditions of the Pafuri and Mapungubwe areas to a eastward displacement of the TTTs. This mechanism should lead to hyperarid conditions in Botswana. However, the 250 years proxy record for the Mabuasehube region of southern Botswana, hinted to wetter conditions induced by positive SST anomalies in the Mozambique Channel (Woodborne et al., 2018).

3. Paleoclimate reconstruction

For obtaining a proxy archive of high temporal resolution for the central area of Botswana, the stable carbon isotope analysis of Chapman wood samples was performed.

3.1. Sample collection. Two samples were collected from the 2 oldest stems (III and VI) of the Chapman baobab. They were labelled CH-3 and CH-6. They were prepared, pretreated and investigated by stable carbon analysis (δ^{13}C) as described in Chapter II.

3.2. Radiocarbon dating and the age model. For obtaining the age model, segments extracted from predetermined positions along the samples were radiocarbon dated and the methodology of Woodborne et al. (2015) was applied.

3.3. Statistical analysis and errors. For diminishing the errors a robust statistical method was used, after Woodborne et al. (2015). Thus, for every age value a 21-year biweight mean was calculated, which highlights the climate variability (Lanzante, 1996).

For all correlations (except with the very short instrumental record for Maun), the 21-year biweight mean was calculated for all used chronologies (Fig. 21). For teleconnection analysis, other statistical methods were applied such as calculating the correlation coefficient and performing significance tests.

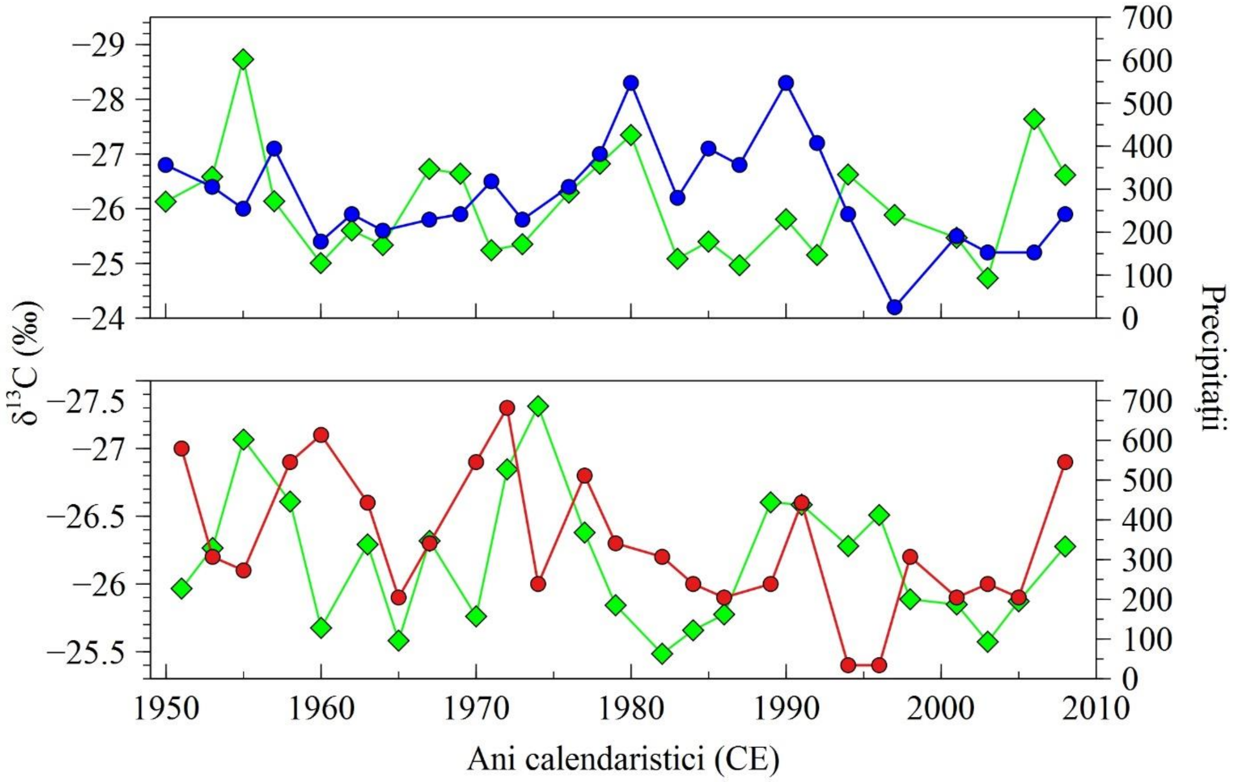

Figure 21. Comparison between the δ^{13}C rainfall record of the Chapman samples (CH-3 blue and CH-6 red) and the instrumental record of Mphale et al. (2014) for Maun (green).

Although the comparison presented in figure 21 shows similarities, an accurate calibration is not possible due to visible lag times and the errors of the age model. Due to the short period available for Maun, the 21-year biweight mean could not be calculated, resulting in statistically insignificant correlations.

A better comparison of the Chapman chronology would be with the rainfall reconstruction for the western part of Zimbabwe spanning over the last 200 years (Therrell et al., 2006). The correlation result of the Zimbabwe record with the instrumental record for Maun is slightly positive and moderately significant for the years 1950-1996. Figure 22 clearly shows that rainfall events in Zimbabwe correspond to similar rainfall events in the central part of Botswana but usually in lower quantity (less rainfall reaches Botswana). According to this graph, rainfall in Botswana is more fluctuating.

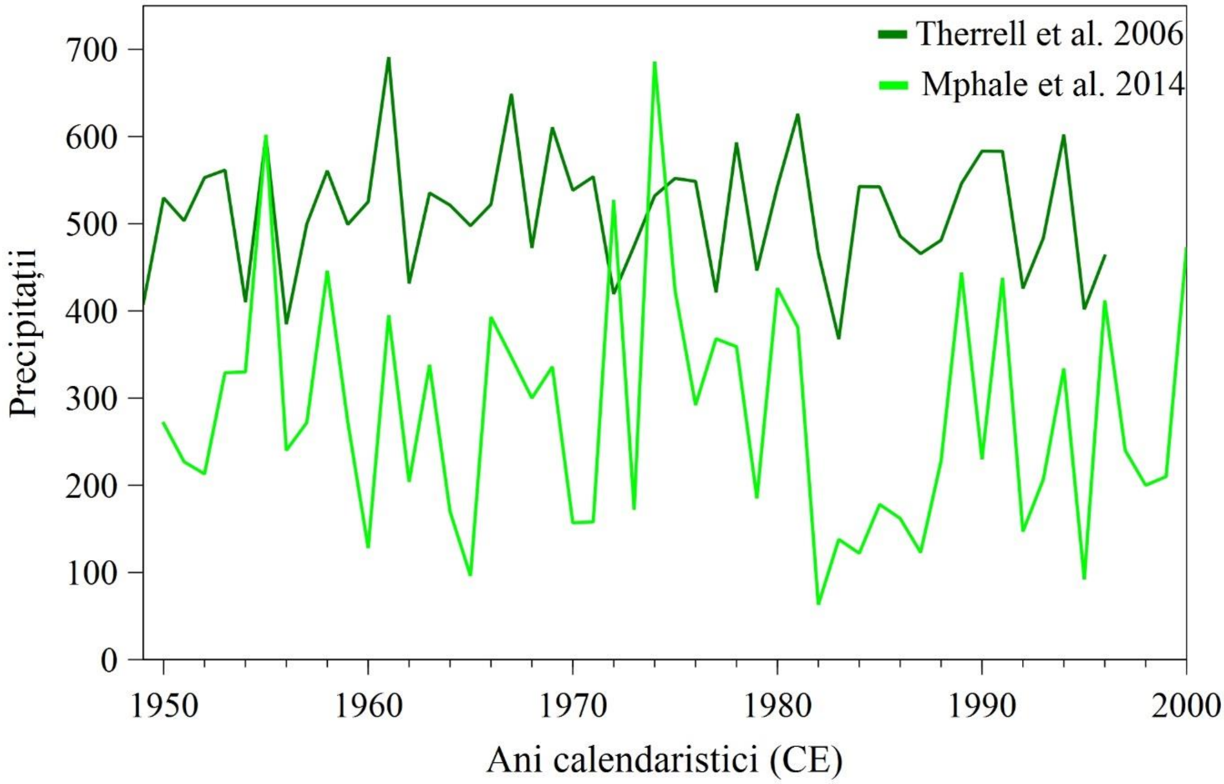

Figure 22. The rainfall reconstruction for Zimbabwe, after Therrell et al. (2006) (dark green) and the instrumental rainfall record for Maun, Botswana, after Mphale et al. (2014) (light green).

The correlation between the Zimbabwe record and the isotope chronologies CH-3 and CH-6 is positive and significant until about 1900, after which the relation becomes weaker and nonsignificant. According to these results, between the years 1800 and the beginning of the 20th century, the wet conditions in Zimbabwe corresponded to more arid conditions in the area of the Chapman baobab; this difference became more prominent after 1900.

3.4. Solar activity influence. The climate of the last millenium, i.e. before the industrial revolution (1760-1840), was mainly modulated by solar activity, which shows a well defined periodicity of the grand minima/maxima cycles of 350-400 years (Zharkova et al., 2017; Luening et al., 2017). Thus, important events that marked past climate archives are the Dalton Minimum (ca. 1797-1825), the Maunder Minimum (ca. 1645–1715; a period of extremely low solar activity (Usoskin et al., 2015)), Spörer Minimum (ca. 1460-1550), Wolf Minimum (ca. 1282–1342), the Medieval Maximum (ca. 1100-1250) and the Oort Minimum (ca. 1010-1050) (Stuiver and Quay, 1980; Hady, 2013; Luening et al., 2017; Zharkova et al., 2017). The 21-year biweight mean of the $\delta^{13}C$ isotopic excursion indicates a mainly dry period, dominated by reduced rainfall, which concurs with the Wolf Minimum (1282–1342). This is the driest period evinced in the Chapman archive for central Botswana and translates into protracted drought.

In Botswana, during the Medieval Warm Period the rainfall level was higher but more variable while temperature was also higher (Tyson et al., 2000).

The aridification trend is obvious after 1900, concurring with several studies that indicate a continuous decrease in rainfall (Kane, 2009; Mphale et al., 2014; Kusangaya et al., 2014). This effect is also replicated in the Chapman record but due to the vast temporal scale, it is clear that the rainfall decrease is not as drastic as previously believed when compared to the droughts registered for the last millenium. Our results corroborate well with a paleoclimate reconstruction for the last 250 years for southern Botswana based on *Vachellia erioloba* wood samples (Woodborne et al., 2018).

Other clear spikes shown in time series such as wet/dry periods that cannot be explained by solar activity, provide a discrimination between the influence of the sun and other parameters that shape the climate of Botswana like sea (paleo)temperatures (ENSO/SST) (Luening et al., 2017).

3.5. ENSO influence. The results of ENSO (Li et al., 2013) correlations with CH-3 is weak positive yet significant until the end of the 19th century. This relationship reversed and became negative after 1900. Although ENSO has an important impact on rainfall in southern Africa, the relationship is still unpredictable (Neukom et al., 2014). ENSO effects can be enhanced or reduced by different factors and the mechanisms have not been elucidated (Jury, 2015).

3.6. SST influence. For analysing the influence of the SST in the Agulhas core region, the paleoclimate coral reconstruction for the Mozambique Channel, Ifaty area, of the last 400 years was used (Zinke et al., 2014). The results show a strong, high positive association of SST with the Chapman records until the end of the 19th century. As in the case of ENSO, the SST influence reversed after 1900. Thus, the TTT movement suggested by Woodborne et al. (2018) for southern Botswana is validated until 1900 by the Chapman record.

3.7. Comparison with the Limpopo reconstruction, South Africa. The comparison between the Chapman data set and the combined rainfall proxy on South African baobabs (Pafuri and Mapungubwe areas) after Woodborne et al. (2016), demonstrates that in north-eastern South Africa, conditions became increasingly arid due to the TTT displacement to the centre of the continent.

The Chapman baobab was the only African baobab on a radius of 10 km, suggesting its survival as a relict in an increasingly dry habitat. It is quite likely that other monumental baobabs collapsed during the last century (Guy, 1967) due to the reversal of the ENSO influence and the SST anomalies of the Mozambique Channel. The collapse of the Chapman baobab and other monumental baobabs in southern Africa can be explained by/attributed to a complex interaction between a gradual decrease in rainfall and a gradual increase in temperature over the last century.

Chapter VII. Climate changes and the demise of the largest and oldest African baobabs

Over the last 15 years, our research team practically dated all known superlative baobabs and other specimens identified for the first time during on-site investigations or following instructions from locals. The number of monumental baobabs is between 65-70 trees. During our investigations another surprising fact was documented, namely the demise of the largest and oldest African baobabs at an unprecedented scale. All trees were located in southern Africa as follows: 5 in South Africa, 4 in Namibia, 3 in Zimbabwe and one each in Botswana, Mozambique and Zambia. Thus, 9 of the oldest 13 and 5 of the largest 6 African baobabs collapsed and died or their oldest stem/stems collapsed and disappeared. Among the victims are the oldest, the most famous and the largest of all African baobabs. From the partially or completely collapsed baobabs, wood samples were collected and investigated by AMS radiocarbon dating. The dating results and the ages of the oldest samples/segments from these superlative baobabs were presented.

Nine individuals exhibit or exhibited a closed ring-shaped structure (Panke, Holboom, Humani Bedford, Matendere, Luna, Lebombo, Lundu, Platland/Sunland, Sagole), while 4 individuals have or had an open ring-shaped structure (Dorslandboom, Glencoe, Makuri Leboom, Chapman). One specimen had an incomplete RSS (Grootboom) and another a cluster structure (Makulu Makete).

The first large African baobab that was AMS radiocarbon dated (Grootboom) collapsed and died in 2004-2005. In the case of other 3 baobabs, all stems collapsed and died (Panke in 2010-2011, Chapman in 2016, Makulu Makete in 2008). For 6 other individuals, the oldest and largest stems collapsed and died (Dorslandboom in 2006, Glencoe in 2009, Makuri Lê boom in 2005, Holboom in 2012, Lundu in 2014, Platland in 2016-2017) but some younger and smaller stems survived.

The superlative baobabs are presented in short:

1. The oldest baobab

The Panke baobab of Matebeleland North, Zimbabwe (Alexander et al., 2000; Mullin, 2003), was a robust tree with a massive trunk and huge branches. The baobab had a closed ring-shaped structure defined by a ring formed by 3 stems around a small false cavity (Fig. 23a). Outside the ring there were 3 additional stems. Chief-inspector Chris Pollard measured the baobab in 1985: cbh = 25,50 m, h = 15,5 m (Cashel, 1995). The baobab volume was estimated to be 400 m^3 (Patrut A. et al., 2018). In 2010, the tall branches started breaking off one by one. The baobab collapsed within a year and a half. The oldest wood sample had a radiocarbon age of 2429 ± 14 BP, which corresponds to a calibrated age of 2455 ± 40 years. This is the oldest angiosperm wood sample ever dated (Fig. 23b). By this value of 2500 years, Panke becomes the oldest African baobab and angiosperm of the world with accurate dating results.

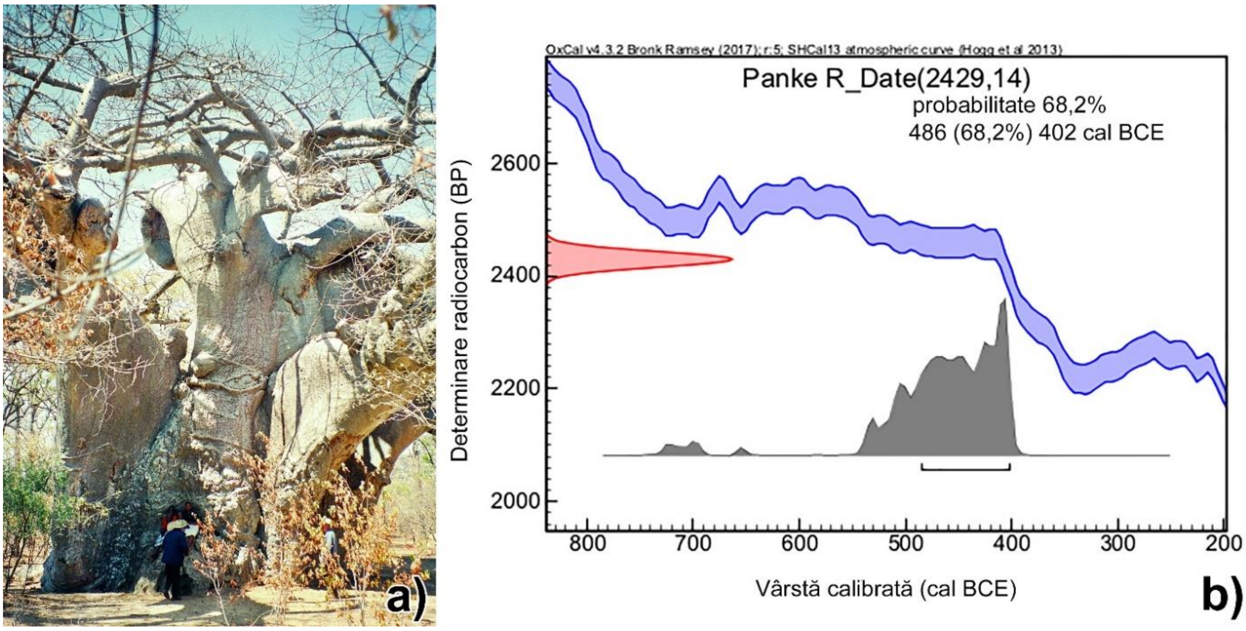

Figure 23. Front view of the Panke baobab (a); (J. Alexander). The calibration cuve of the oldest sample originating from Panke (b).

2. The most famous baobab

The most famous baobab was undoubtedly the historic Chapman baobab presented in extenso in chapter VI (Fig. 24).

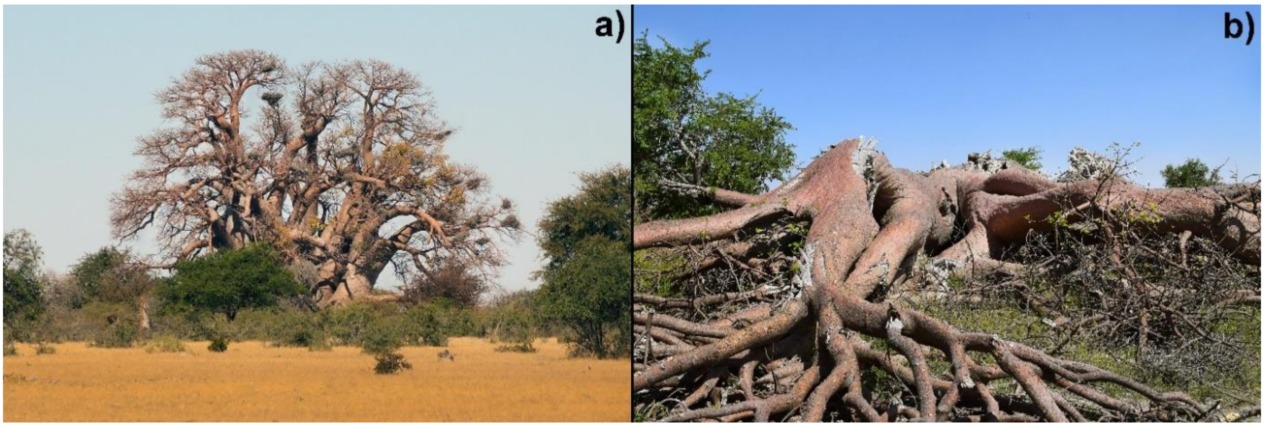

Figure 24. The Chapman baobab was a beacon for travellers passing through the salt pans (a). All 6 stems toppled simultaneously in the morning of January 7, 2016 (b).

3. The largest baobab

The Platland tree, also known as the Sunland baobab, was the largest African baobab in terms of volume. Platland is located in the Limpopo province, South Africa. The baobab had an unusual structure, namely a double closed ring-shaped structure with 2 interconnected false cavities. Thus, the baobab had 2 distinct units (Patrut A. et al., 2010a; 2011; 2017b). Measurements revealed the following dimensions: h = 18,9 m, cbh = 34,11 m and V = 501 m^3. Plantland is the most visited baobab of South Africa due to the „Sunland pub baobab" built inside the large false cavity (Fig. 25). The calculated age for unit I is of only 800 years and for unit II, about 1100 years (Patrut A. et al., 2017b). Starting May 2016, unit I began to split and collapse. It is uncertain whether the smaller yet older unit II will survive.

Figure 25. Platland/Sunland baobab consisted of two distinct units, that formed a double closed ring-shaped structure with two interconnected false cavities (a). A bar/pub used to function inside the cavity (b).

Dorslandboom. The Dorslandboom baobab of Namibia, was presented in chapter IV. Dorslandboom is the second oldest baobab in the world after Panke, with 2100 years (Fig. 26).

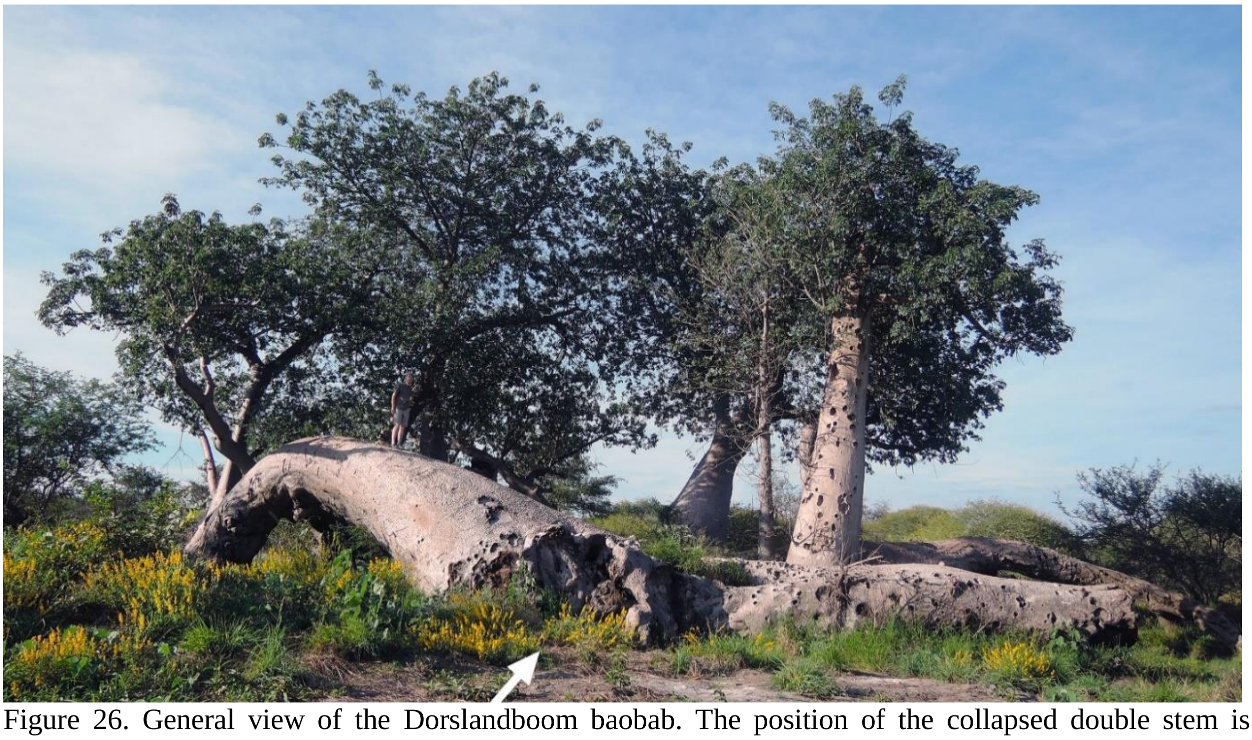
Figure 26. General view of the Dorslandboom baobab. The position of the collapsed double stem is indicated by a white arrow.

Glencoe. The Glencoe tree of South Africa is on the third place with an age of over 2000 years.

Holboom. The Holboom baobab is located in Namibia. This baobab has the largest cbh of the genus (35,10 m). Holboom is the fourth oldest and sixth largest African baobab with V = 340 m^3. Its maximum age is 1800 years.

Humani Bedford. The Humani Bedford baobab of Zimbabwe, is the oldest living African baobab at the age of 1800 years.

Makuri Lê boom. The fifth African baobab regarding theage is Makuri Lê boom, also from Namibia. This spectacular tree consists of 12 stems and has a calculated age of about 1800 years (Patrut R.T. et al., 2020).

Grootboom. Grootboom baobab of Namibia is the sixth African baobab regarding the age and the fifth in terms of volume (Patrut A. et al., 2007). At the age of 1600 years, Grootboom was the tallest African baobab ever measured.

Matendere. Matendere Big baobab, is the eighth oldest African baobab and was presented in chapter V. The baobab is about 1550 years old.

Luna. Luna tree is located in South Africa. The age of the baobab was estimated to be up to 1600 years (Patrut A. et al., 2015d).

Lebombo. The Lebombo baobab was described in chapter IV. The maximum age of Lebombo is 1400 years. Thus, Lebombo is the tenth oldest African baobab.

Makulu Makete. The Makulu Makete Big baobab is the twelfth oldest baobab after Chapman. The age was found to be 1250 years.

Lundu. Lundu is the thirteenth oldest baobab and is located in Zambia. The Lundu baobab has a maximum age of 1250 years.

Sagole. The Sagole baobab of South Africa is the second largest African baobab in terms of volume, right after Platland/Sunland (V = 414 m^3). Thus, Sagole is the largest living African baobab (Patrut A. et al., 2017b; 2017e). An age of 850 years was determined for this baobab.

The demise of the majority of the largest and oldest baobabs of southern Africa over the last 15 years is an important warning without precedent. All reported collapses occurred on a very large area, many of the affected baobabs being solitary specimens over many kilometers. The lack of any sign of a disease and the vast area of occurrence demonstrates the phenomenon is not caused by an epidemic (Fig. 27). Field investigations and discussions with locals indicate a mortality increase (apparently due to natural causes) among younger and smaller mature baobabs. It is unlikely that recent rainfall variability is the culprit for the demise of these monumental trees as millennial baobabs have survived wetter and drier conditions in the past. Nevertheless, temperature increase may be an important contributing factor. Large old trees are most affected by drought (Bennett et al., 2015).

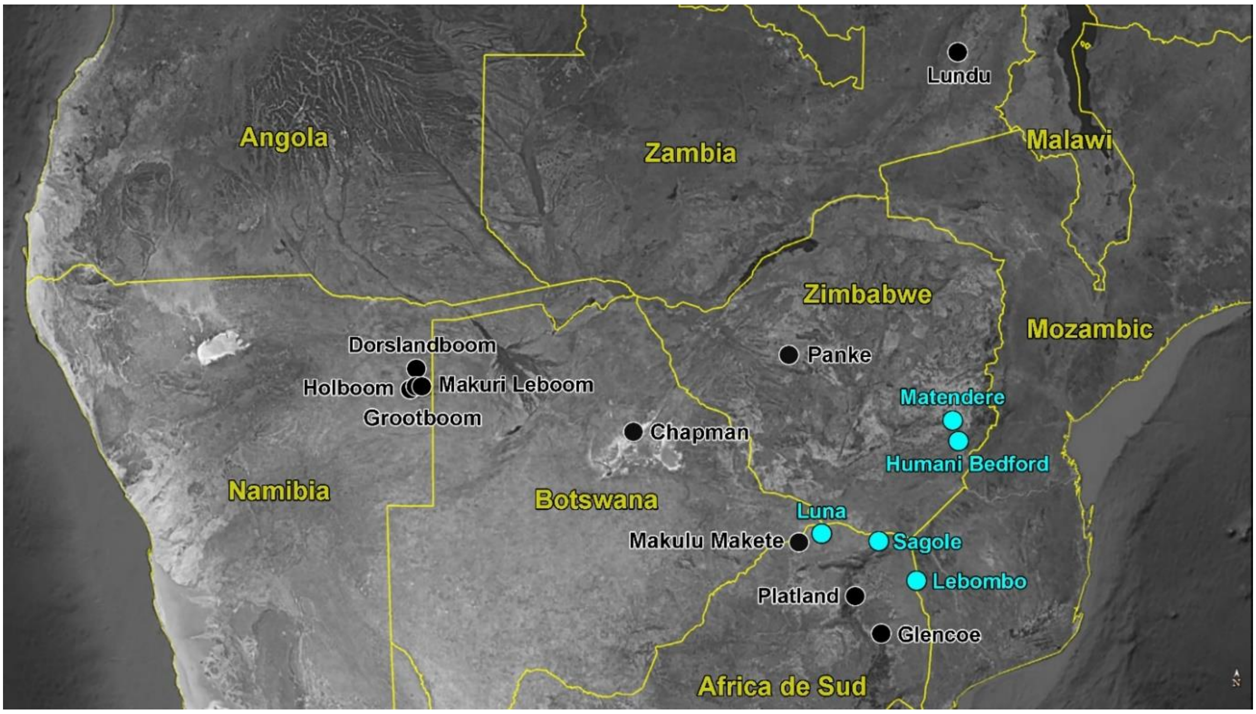

Figure 27. The location of the superlative African baobabs in southern Africa is shown with black dots (for deceased or partially collapsed specimens) and with blue dots (for live baobab that are in a relatively good state); (adapted from Google Earth).

Paleoclimate evidence shows that in southern Africa baobabs also survived colder conditions. It is very likely that in the context of climate change, a temperature increase combined with a rainfall decrease (leading to protracted droughts) had a decisive impact for the collapse of the oldest and largest baobab in the world.

Chapter VIII. Conclusions

Due to unexpected results, the studies on radiocarbon dating of baobabs were continued with a focus on age determination, architecture and growth rates.

The ability to generate multiple stems during their life cycle, allows baobabs to attain increasingly complex architectures, which enables them to reach extraordinary sizes and very old ages. All African baobabs with a circumference larger than 14 m consist of several stems. The baobab of Warang was investigated and it was found to be the specimen with the highest number of stems identified for the *Adansonia* genus. The baobab of Warang has 18 partially fused stems and the largest circumference ever recorded for an African baobab in the northern hemisphere: 28,69 m.

The radiocarbon investigation of the baobab of Warang also identified the origin of odd-looking stems, which are triangular or trapezoid in horizontal section. Thus, 6 out of the 18 stems of the Warang baobab are false ones. False stems emerge from a large adjacent stem and extend obliquely by branching out, while the lower part merges with the radicular system over time. The oldest age of a false stem is located in the upper part, close to the stem from which it emerged.

Ring-shaped structures are unusual architectures of the *Adansonia* genus. Two main types were discovered, i.e. the open and closed ring-shaped structure. For the open ring-shaped structure, individual stems can be easily identified, being fused only at the base. In the case of closed ring-shaped structures, several (almost) perfectly fused stems are disposed in a circle around an empty space, which was called false cavity. The difference between natural and false cavities can be determined by the presence of bark on the cavity walls. False stems tend to become smaller over time (due to stem growth), while natural cavities become larger (due to continuous decay). The typical age sequence of samples collected from the inner cavity (towards the exterior) but also from the exterior of the trunk (towards the cavity) present the same anomaly, namely an increase in age values up to a certain point into the wood, after which it decreases towards the opposite direction. The baobab of Warang has an interesting architecture composed of a cluster structure and a closed ring-shaped structure, which is defined by 3 stems around a false cavity. The age of this Senegalese baobab is relatively modest, of only 500 ± 50 years. Ring-shaped structures enable baobabs to reach millennial ages and remarkable sizes.

Radiocarbon dating results showed that in certain cases, the outermost growth rings are very old due to the stop of radial stem growth. This phenomenon does not seem to affect the individual, which continues to flush leaves, develop flowers and pods. The dating results of 7 baobabs of the *Adansonia* genus were presented and discussed. Four major factors that can contribute to the onset of the growth stop phenomenon were identified: (i) stress induced by harsh conditions, such as severe climate changes; (ii) old age; (iii) maintaining a stable architecture; (iv) shock induced by major trauma. Growth stop was associated with the ability of baobabs to store a large quantity of water in their trunks. Baobabs whose stems have stopped their growth along the circumference can survive in this state for more than 6 centuries. Growth stop was documented in *A. digitata*, *A. grandidieri* and *A. rubrostipa*.

The Savé Valley Conservancy of Zimbabwe hosts thousands of African baobabs. Four outstanding specimens were investigated by radiocarbon dating. All baobabs had a circumference larger than 23 m and exhibited closed ring-shaped structures with false cavities inside. The ages of the monumental baobabs of Savé Valley are: 1550 ± 100 years for the Matendere baobab, 1200 ± 100 years for both Chishakwe and Mokore baobabs. The maximum age calculated for the Humani Bedford baobab is 1800 years, which makes it the oldest living baobab and angiosperm in the world with accurate dating results.

During field investigations off the beaten track, a huge *A. grandidieri* was discovered in the Morombe area. Measurements show that this Grandidier baobab, the Grand Reniala of Isosa, is the largest *Adansonia* specimen in terms of volume. This superlative baobab has a wood volume of 540 m^3, by which it becomes the largest living angiosperm and baobab. The age determination enabled the calculation of growth rates, which indicate a minimum age of 1000 ± 100 years for the Grand Reniala of Isosa.

In January 2016, the sudden collapse of the historic Chapman baobab was witnessed. The baobab had an open ring-shaped structure consisting of 6 main large stems, which were fused at the base. The stems belonged to 3 distinct generations of 1350-1400 (stem III), 800-1000 (stems I, V and VI) and 500-600 years (stems II and IV). Only stem III was found to belong to the original ring. Large baobabs close to the end of their life cycle collapse gradually over several years. Thus, the collapse of all stems of the Chapman baobab was an uncommon event and the causes of its demise were investigated. Four main contributing factors were identified: (i) the size increase of the natural cavity; (ii) the low water content of stems associated with protracted drought caused by the very intense El Niño event; (iii) the recent increase of the leaning degree of stems; (iv) old age.

After the demise of the Chapman baobab, samples were collected for the purpose of paleoclimate reconstruction by stable carbon isotope analysis. A high-resolution rainfall proxy for the central region of Botswana spanning over the last millennium was obtained. The solar minima and maxima but also historical droughts of the last millennium are replicated by the isotopic series. The climate archive demonstrates that, in the past, there were drier and wetter conditions for central (and northern) Botswana. The climate relationship with El Niño–Southern Oscillation (ENSO) and Sea Surface Temperature (SST) in the Agulhas Core Region reversed over the last century. Rainfall amount was overall much higher in South Africa but lower in Botswana than present day.

In recent years, an alarming fact was recorded during our research, namely the partial or total collapse of mature African baobabs, especially monumental ones, i.e. very old and/or large specimens. Thus, since 2005, 9 out of the 13 oldest and 5 out of the 6 largest African baobabs partially or totally collapsed. This demise of the largest and oldest baobabs (or of their oldest stem(s)/parts) documented in southern Africa was not due to an epidemic, nor a consequence of old age. The collapses are associated with climate modifications, attributed to a complex interaction between the gradual rainfall decrease and gradual temperature increase in recent times, which trigger changes of the climate regime.

Scientific performance

1. Published papers

1.1 Published results, which were included in chapters of the Ph.D. thesis:

- Chapter III:

1. Patrut A., Garnaud S., Ka O., **Patrut R.T.**, Diagne T., Lowy D.A., Forizs E., Bodis J., von Reden K.F., African baobabs with a very large number of stems and false stems: Radiocarbon investigation of the baobab of Warang, Studia UBB Chemia, 2017, LXII, 1, 111-120. doi:10.24193/subbchem.2017.1.09.

- Chapter IV:

2. Patrut A., Woodborne S., von Reden K.F., Hall G., **Patrut R.T.**, Rakosy L., Danthu P., Leong Pock-Tsy J.-M., Lowy D.A., Margineanu D., The growth stop phenomenon of baobabs (*Adansonia* spp.) identified by radiocarbon dating, Radiocarbon, 2017, 59(2), 435-448. doi:10.1017/RDC.2016.92.

- Chapter V:

3. Patrut A., Rakosy L., **Patrut R.T.**, Ratiu I.A., Forizs E., Margineanu D., von Reden K.F., Radiocarbon dating of a very old baobab from Savé Valley, Zimbabwe, Studia UBB Chemia, 2016, LXI, 4, 7-20. (factor de impact ISI: 0.246 AIS 0.055).

4. Patrut A., **Patut R.T.**, Rakosy L., Lowy D.A., Margineanu D., von Reden K.F., Radiocarbon investigation of the superlative African baobabs from Savé Valley Conservancy, Zimbabwe, Studia UBB Chemia LXIV(2): 7-14, 2019, doi: 10.24193/subbchem.2019.2.35.

5. **Patrut R.T.**, Patrut A., Leong Pock-Tsy J.-M., Woodborne S., Rakosy L., Danthu P., Ratiu I.A., Bodis J., von Reden K., Radiocarbon investigation of a superlative Grandidier baobab, the Big Reniala of Isosa, Studia UBB Chemia LXIV(4): 131-139, 2019, doi: 10.24193/subbchem.2019.4.10.

- Chapter VI:

6. Patrut A., Woodborne S., **Patrut R.T.,** Hall G., Rakosy L., Winterbach C., von Reden K.F., Age, growth and death of a national icon: the historic Chapman baobab of Botswana, Forests 10(11): 983, 2019, doi: 10.3390/f10110983.

- Chapter VII:

7. Patrut A., Woodborne S., **Patrut R.T.**, Hall G., Rakosy L., von Reden K.F., Lowy D.A., Margineanu D., Radiocarbon dating of African baobabs with two false cavities: The investigation of Luna tree, Studia UBB Chemia, 2015, LX, 4, 7-20.

8. Patrut A., Woodborne S., **Patrut R.T.**, Rakosy L., Lowy D.A., Hall G., von Reden K.F., The demise of the largest and oldest African baobabs, Nature Plants, 2018, doi.org/10.1038/s41477-018-0170-5.

9. Patrut A., **Patrut R.T.**, Van Pelt R., Lowy D.A., Forizs E., Bodis J., Margineanu D., von Reden K.F., Radiocarbon dating of a very large African baobab from Limpopo, South Africa: Investigation of the Sagole Big tree, Studia UBB Chemia, 2017, LXII, 2, Tom II, 355-364. doi:10.24193/subbchem.2017.2.28.

10. Patrut A., Woodborne S., **Patrut R.T.**, Rakosy L., Hall G., Ratiu I.A, von Reden K.F., Final radiocarbon investigation of Platland tree, the biggest African baobab, Studia UBB Chemia, 2017, LXII, 2, Tom II, 347-354. doi:10.24193/subbchem.2017.2.27. (

11. **Patrut R.T.**, Patrut A., Rakosy D., Rakosy L., Löwy D.A., Bodis J., von Reden K., Radiocarbon dating of Makuri Lê boom, a very old African baobab from Nyae Nyae, Namibia, Studia UBB Chemia LXV(2): 149-159, 2020, doi: 10.24193/subbchem.2020.2.12.

1.2. Other papers published during the Ph.D. stage:

12. Patrut A., Patrut R.T., Danthu P., Leong Pock-Tsy J.-M., Rakosy L., Lowy D.A., von Reden K.F., AMS radiocarbon dating of large za baobabs (*Adansonia za*) of Madagascar, PLoS ONE, 2016, 11(1), e0146977. doi:10.1371/journal.pone.0146977.

13. Patrut A., **Patrut R.T.**, Rakosy L., Bodis J., Lowy D.A., Forizs E., von Reden K.F., African baobabs with double closed ring-shaped structure and two separate false cavities: Radiocarbon investigation of the baobab of Golconda Fort, Studia UBB Chemia, 2016, LXI, 4, 21-30, doi: 10.24193/subbchem.2017.1.09.

14. Woodborne S., Hall G., Jones C.W., Loader N.J., Patrut A., **Patrut R.T.**, Robertson I., Winkler S.R., Winterbach C.W., A 250-year, proxy rainfall record from southern Botswana, Studia UBB Chemia, 2018, LXIII, 1, 109-123. doi:10.24193/subbchem.2018.1.09.

15. Patrut A., **Patrut R.T.**, L. Rakosy, I.A. Raţiu, D.A. Lowy, J. Bodis, K.F. von Reden, Radiocarbon dating of the old ash of Aiton, Romania, Studia UBB Chemia, 2018, LXIII.

16. Patrut A., Robu N., Savu V., **Patrut R.T.**, Rakosy L., Ratiu I.A., Lowy D.A., Margineanu D., von Reden K.F., Radiocarbon investigation of the pedunculate oak of Botoşana, Studia UBB Chemia, 2018, LXIII, 4, 13-20.

17. Patrut A., Garg A., Woodborne S., **Patrut R.T.**, Rakosy L., Ratiu I.A., Lowy D.A., Radiocarbon dating of two old sacred baobabs from India, PLOS ONE 15(1): e0227352, doi: 10.1371/journal.pone.0227352.

2. International scientific conferences in which the Ph.D. student partook:

-16-20 November 2015: International conference Radiocarbon-22, Dakar, Senegal
-14-18 August 2017: International conference AMS-14, Ottawa, Canada
-25-29 September 2017: International conference PMIP4, Stockholm, Suedia
-17-22 June 2018: International conference Radiocarbon-23, Trondheim, Norvegia
-15-17 December2019: International congress on baobabs, Morondava, Madagascar

3. Presentations at international scientific conferences:

- 16-20 November 2015: International conference Radiocarbon-22, Dakar, Senegal; 2 poster presentations entitled **The growth stop phenomenon of baobabs (*Adansonia spp.*) identified by AMS radiocarbon dating** (authors: Patrut A., Woodborne S., von Reden K.F., Hall G., **Patrut R.T.**, Rakosy L., Danthu P., Leong Pock-Tsy J.-M., Lowy D.A., Margineanu D.) and **Radiocarbon dating of African baobabs (*Adansonia digitata*) with ring-shaped structures and false cavities** (authors: **Patrut R.T.**, von Reden K.F., Woodborne S., Rakosy L., Patrut A., Hall G., Garnaud S., Lowy D.A., Margineanu D.)
- 14-18 August 2017: International conference AMS-14, Ottawa, Canada; 2 poster presentations entitled **AMS radiocarbon dating of the largest and oldest African baobabs of Senegal** (authors: Patrut A., **Patrut R.T.**, Woodborne S., von Reden K., Ka O., Garnaud S., Lowy D.A.) respectiv **AMS radiocarbon dating of baobabs from dwarf baobab groves** (authors: Patrut A., Woodborne S., **Patrut R.T.**, Rakosy L., Hall G., von Rden L, Danthu P., Leong Pock-Tsy J.-M., Margineanu D.)
- 25-29 September 2017: International conference PMIP4, Stockholm, Suedia; a poster presentations entitled **Comparing a high spatial/temporal resolution rainfall proxy dataset from southern Africa with a last millennium simulation** (authors: Woodborne S., Zhang Q., Hall G., Hamilton T., Patrut A., **Patrut R.T.**);
- 17-22 June 2018: International conference Radiocarbon-23, Trondheim, Norvegia; a poster presentation entitled **AMS radiocarbon dating of very large African baobab trees from Savé Valley, Zimbabwe** (authors: Patrut A, **Patrut R.T.**, Rakosy L., von Reden K.F., Lowy D.A., Margineanu D.) and an oral presentation by Roxana Patrut, entitled **Main results of thirteen years of radiocarbon investigation of large and old African baobab trees** (authors: **Patrut R.T.**, Patrut A., Woodborne S., Rakosy L., von Reden K., Lowy D.A., Hall G, Ratiu I.-A.)
- 15-17 December 2019: International congress on baobabs, Morondava, Madagascar, oral presentation by A. and Roxana Patrut entitled: **Dimensions, âge, architecture, croissance, mort et conservation des plus gros *Adansonia grandidieri*** (authors: Patrut A., **Patrut R.T.**, Leong Pock-Tsy J.-M., Danthu P., Woodborne S., Rakosy L.)

4. Research projects in which the Ph.D. student partook as a team membre:

1. September 2013-December 2016, no: 76/2013 code: PN-II-ID-PCE-2012-4-0393, research project title: New research in dendrochronology and environmental climate change by using AMS/CFAMS radiocarbon dating and stable isotope analysis.

2. July 2017-December 2019, no: 90/2017, code: PN-III-P4-ID-PCE-2016-0776, research project title: Age, growth and architecture of monumental angiosperm trees assessed by AMS radiocarbon investigation and climate research performed by stable isotope analysis of wood samples collected from such trees.

5. Research internships of the Ph.D. student:

1. Research internship at Stable Isotope Facility (University of Pretoria) during February-April 2017.

2. Research internship at the Stable Isotope Facility (University of Pretoria) and iThemba LABS during October-November 2017.

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