Quaternary Science Reviews 134 (2016) 92–99

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

# Rapid human-induced landscape transformation in Madagascar at the end of the first millennium of the Common Era

Stephen J. Burns [a,*], Laurie R. Godfrey [b], Peterson Faina [c], David McGee [d], Ben Hardt [d], Lovasoa Ranivoharimanana [c], Jeannot Randrianasy [c]

[a] Department of Geosciences, 611 North Pleasant Street, University of Massachusetts, Amherst, MA 01003, USA
[b] Department of Anthropology, 240 Hicks Way, University of Massachusetts, Amherst, MA 01003, USA
[c] Département de Paléontologie et d'Anthropologie Biologique, Faculté des Sciences, B.P 906 – 101 Antananarivo, Madagascar
[d] Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

A R T I C L E I N F O

*Article history:*
Received 23 October 2015
Received in revised form
8 January 2016
Accepted 12 January 2016
Available online 21 January 2016

*Keywords:*
Paleoecology
Paleoclimatology
Stable isotopes
Speleothems
Madagascar

A B S T R A C T

The environmental impact of the early human inhabitants of Madagascar remains heavily debated. We present results from a study using two stalagmites collected from Anjohibe Cave in northwestern Madagascar to investigate the paleoecology and paleoclimate of northwestern Madagascar over the past 1800 years. Carbon stable isotopic data indicate a rapid, complete transformation from a flora dominated by $C_3$ plants to a $C_4$ grassland system. This transformation is well replicated in both stalagmites, occurred at 890 CE and was completed within one century. We infer that the change was the result of a dramatic increase in the use of fire to promote the growth of grass for cattle fodder. Further, stalagmite oxygen isotope ratios show no significant variation across the carbon isotope excursion, demonstrating that the landscape transformation was not related to changes in precipitation. Our study illustrates the profound impact early inhabitants had on the environment, and implies that forest loss was one trigger of megafaunal extinction.



## 1. Introduction

Considerable controversy remains over the timing, causes and magnitude of forest and woodland loss in Madagascar (McConnell and Kull, 2014). For much of the past century the prevailing view was that prior to human arrival forest and woodland covered 90% of the island (Humbert, 1927), and that the loss of Madagascar's forests was due to human activity (Perrier de la Bâthie, 1921). Recent studies, however, suggest that Madagascar's grasslands are a natural part of the island's ecosystem (Burney, 1987; Quéméré et al., 2012) and may even date to the late Miocene (Bond et al., 2008). Indeed, some authors question the entire narrative of extensive alteration of the landscape by early human activity (Klein, 2002; Kull, 2000). Whether forest loss was the result of early human activity (Gade, 1996), was post-Colonial (Jarosz, 1993) or was, in fact, not significant (Klein, 2002) also has important implications for the causes of the decline and ultimate disappearance of Madagascar's endemic megafauna, which mainly occurred prior to European contact (Burney et al., 2004; Crowley, 2010). Answering these questions is difficult because there are few high-resolution, well-dated studies of Madagascar's paleoclimate and paleoecology.

Speleothems, calcium carbonate cave deposits, offer an opportunity to investigate both ecosystem and climate change in the same archive via stable carbon and oxygen isotope ratios, respectively. Carbon isotope ratios are sensitive to the ratio of surface flora that utilize the $C_3$ (woody taxa) versus $C_4$ (grasses) photosynthetic pathways. In the tropics, the oxygen isotope ratio of precipitation is, empirically and mechanistically, strongly correlated with the amount of precipitation, a signal that is captured in the oxygen isotope ratios of speleothem calcite. Speleothems also offer unusually robust chronological control through disequilibrium U-series dating techniques. To investigate the recent environmental and climate history of Madagascar, we collected two actively growing stalagmites, M14-AB2 and M14-AB3, from Anjohibe Cave (15.54°S, 46.89°E, 131 masl) in northwestern Madagascar in 2014.

## 2. Setting

Ajohibe Cave is part of a karst system formed within the Eocene

* Corresponding author.
*E-mail address:* sburns@geo.umass.edu (S.J. Burns).

http://dx.doi.org/10.1016/j.quascirev.2016.01.007
0277-3791/

limestone plateau (Besairie and Collignon, 1972) of northwestern Madagascar (Fig. 1). Anjohibe ('big cave' in Malagasy) consists of 5.3 km of cave passages with over two dozen openings (Burney et al., 1997). Samples AB2 and AB3 (Fig. 2) were taken ~1 km from the main entrance to the cave and approximately 400 m distant from one another (for a map of the cave see Burney et al., 1997). The samples were collected in October, at the end of the dry season, and there were very few active drips within the cave. Neither sample was beneath an active drip at the time of collection. Both samples appeared to be still actively or very recently growing, however, based on the clean, white calcite deposits on the top of the stalagmites.

The landscape overlying the cave is presently palm savannah (Fig. 1) with small patches of mesic forest in wetter areas (Burney et al., 1997). Rainfall in the region is highly seasonal. At the nearest weather station, Mahajanga, which is ~70 km from the cave, over 80% of the mean annual rainfall (1496 mm) occurs in the four month period from December through April. Mean monthly temperature varies 3.2 °C throughout the year, with an annual mean of 27.2 °C (data from http://www.ncdc.noaa.gov/data-access).

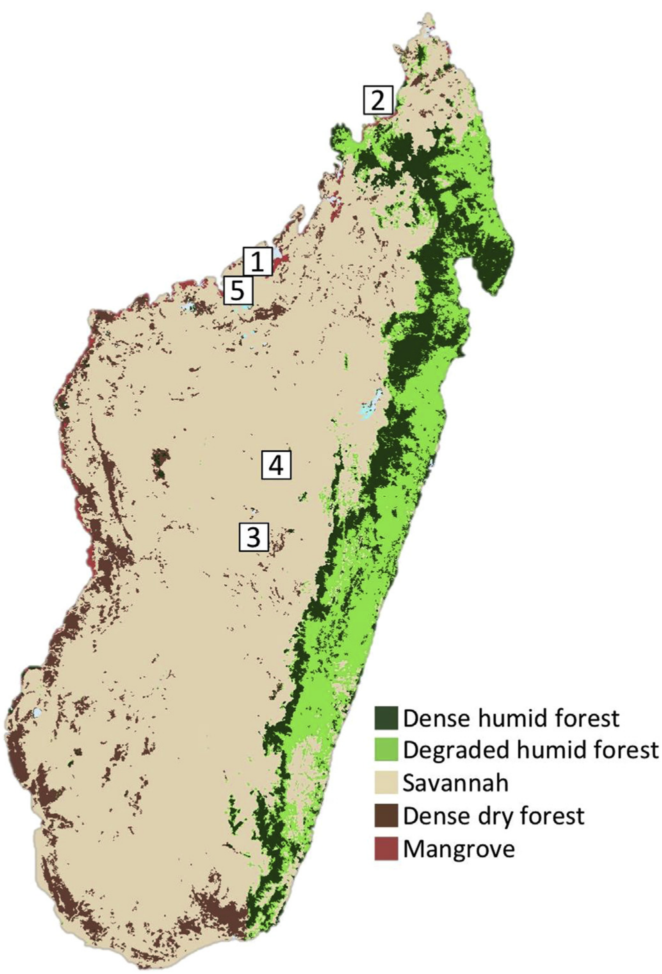


**Fig. 1. Madagascar ecosystems and site location**. This map shows the present distribution of major ecosystems in Madagascar (Mayaux et al., 2000) and the locations of the study area and lake study sites mentioned in the text: 1. Anjohibe Cave, 2. Lake Amparihibe (Burney et al., 2004), 3. Lake Tritrivakely (Gasse and Van Campo, 1998), 4. Lake Kavitaha (Burney, 1987) and 5. Lake Mitsinjo (Matsumoto and Burney, 1994).


**Fig. 2. Sample photographs**. Photograph with scale of cut and polished slabs of samples AB2 and AB3 showing internal layering.

## 3. Methods

The two speleothems were halved along the growth axis and subsampled along growth layers for radiometric dating using uranium-thorium (U–Th) techniques by multi-collector, inductively coupled plasma mass spectroscopy (MC-ICP-MS) (Cheng et al., 2013). Carbon and oxygen stable isotope ratios were measured on 266 samples from AB2 and 173 samples from AB3. Temporal resolution of the stable isotope time series is less than 10 years for all of M14-AB2 and M14-AB3. Age models (Fig. 3) were constructed using 8 age determinations from AB2 and 10 from AB3 (Table 1) and assuming an age for the top of each stalagmite of 2014 CE.

### 3.1. O and C stable isotope analyses

The stable oxygen and carbon isotope ratio measurements were