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ORIGINAL ARTICLE

Forging Ahead By Land and By Sea: Archaeology and Paleoclimate Reconstruction in Madagascar

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Abstract Madagascar is an exceptional example of island biogeography. Though a large island, Madagascar's landmass is small relative to other places in the world with comparable levels of biodiversity, endemicity, and topographic and climatic variation. Moreover, the timing of Madagascar's human colonization and the social-ecological trajectories that followed human arrival make the island a unique case study for understanding the dynamic relationship between humans, environment, and climate. These changes are most famously illustrated by the mass extinction of the island's megafauna but also include a range of other developments. Given the chronological confluence of human arrival and dramatic transformations of island ecologies, one of the most important overarching questions for research on Madagascar is how best to understand the interconnections between human communities, the environment, and climate. In this review paper, we contribute to the well-established discussion of this complex question by highlighting the potential for new multidisciplinary research collaborations in the southwest part of the island. Specifically, we promote the comparison of paleoclimate indicators from securely dated archaeological and paleontological contexts with Western Indian Ocean climate records, as a productive way to improve the overall resolution of paleoclimate and paleoenvironmental reconstruction for the island. Given new archaeological findings that more than double the length of Madagascar's human occupation, models of environmental transformation post-human arrival must be reassessed and allow for the possibility of slower and more varied rates of change. Improving the spatial and temporal resolution of paleoclimate reconstruction is critical in distinguishing anthropogenic and climate drivers of environmental change. It will also increase our capacity to leverage archaeological and paleoclimate research toward resolving modern challenges, such as environmental conservation and poverty alleviation.

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Résumé Madagascar représente un cas exceptionnel de biogéographie insulaire. Bien que ce soit une très grande île, la superficie de Madagascar est relativement petite quand on la compare à d'autres régions ayant des taux similaires de biodiversité et d'endémicité, et témoignant d'une telle diversité topographique et climatique. Par ailleurs, la période pendant laquelle s'est opérée la colonisation humaine de Madagascar, ainsi que les développements socio-écologiques qui se sont ensuivis font de cette île un objet d'étude idéal pour comprendre les dynamiques de la relation entre les humains, l'environnement et le climat. Ces changements sont notoirement illustrés par la disparition totale de la mégafaune de l'île, mais d'autres évolutions importantes sont également à souligner. Etant donné la convergence chronologique de l'arrivée de l'Homme et des transformations radicales de l'écologie de l'île, une des questions centrales de la recherche sur Madagascar vise la compréhension de la nature de l'interaction entre les communautés humaines, l'environnement et le climat. Dans cet article, nous contribuons à la discussion déjà éprouvée de cette question difficile en dévoilant de nouvelles opportunités de collaborations multidisciplinaires, notamment dans la région sud-ouest de Madagascar. Nous proposons en particulier d'utiliser la comparaison de données paléoclimatiques provenant de sites archéologiques et paléontologiques ayant une chronologie établie avec les archives climatiques de l'océan Indien comme un moyen efficace d'améliorer la résolution des reconstructions paléoclimatiques et paléoenvironnementales de l'île. Considérant les dernières datations archéologiques qui doubleraient la durée de l'occupation humaine de Madagascar, nous nous devons de réexaminer les théories de transformation environnementale causée par l'arrivée de l'Homme et d'envisager la possibilité de changements qui se seraient opérés plus lentement et de diverses manières. L'amélioration de la résolution spatiale et temporelle des reconstructions paléoclimatiques à Madagascar est essentielle pour permettre de faire la différence entre les facteurs anthropiques et les facteurs climatiques, quant à leur rôle comme source de transformations environnementales de l'île. Cela nous permettra également de nous appuyer sur le savoir archéologique et paléoclimatique afin de répondre aux grands défis de nos jours, tels que la conservation de l'environnement et la lutte contre la pauvreté.

Keywords Madagascar · Archaeology · Paleoclimate · Island colonization · Isotopes · Corals · Ratite eggshell

Introduction

In Madagascar, as is the case with many islands around the world, the period coinciding with the arrival and subsequent trajectories of human communities has been characterized by an increase in the rate of environmental change and by a transformation of the island's diverse ecologies (Rick *et al.* 2013). However, it has been particularly difficult to reach consensus in understanding these transformations in Madagascar and in describing the coevolution of the island's human and natural communities in the last few thousand years.

This paper is inspired by the review of Madagascar's natural and culture history most recently put forth (Dewar and Richard 2012) and hopes to contribute to its thought-provoking discussion. In light of the more recent publication of new archaeological findings that more than double the recorded length of human occupation of the island (Dewar *et al.* 2013), we reflect on the challenges that continue to frustrate consensus on the extent and nature of anthropogenic impact over time. Moreover, we emphasize that the reporting of new dates for Madagascar's earliest human settlement makes the present moment ripe for establishing new research collaborations between archaeologists, paleontologists, paleoclimatologists, and others. As an example of future directions and to stimulate additional research collaborations, research in southwest Madagascar will be considered. A convergence of field research projects and growing bodies of archaeological, paleontological, paleoclimatological, and modern subsistence data from the southwest set the region apart and promise to lend important new insights.

Three broad questions emerge from the fields of archaeology, paleontology, paleoclimatology, evolutionary biology, and other environmental sciences in their efforts to elucidate Madagascar's past. The first question is what is the extent of the changes in Madagascar's climate and environment, particularly over the last 4,000 to 5,000 years since the island's earliest known human settlement (Dewar *et al.* 2013). The second is how are these changes related to human arrival and impact. Finally, the third question is how best to study the dynamic interplay between humans, environment, and climate and improve the resolution of paleoclimate and paleoenvironmental reconstruction.

The following sections touch on the first two questions by way of a brief discussion of recent archaeological findings in Madagascar. In response to the third question, part III describes research potential in the southwest region and advocates systematic interpretation of paleoclimate indicators from securely dated archaeological and paleontological contexts alongside existing Western Indian Ocean (WIO) climate records derived from corals, speleothems, and other marine and terrestrial proxies. Cross-referencing paleoclimate indicators from archaeological and paleontological contexts with existing WIO climate records will enable localized verification of regional climate trends (Gunn and Folan 2000). Given Madagascar's tremendous biogeographic diversity, such an approach will test the suitability of regional climate records for describing the climate regimes of individual localities and will improve the resolution of regional climate archives. Moreover, the comparison of archaeological, paleontological, and paleoclimate datasets will offer a well-resolved climate backdrop against which diachronic human action in Madagascar can be more richly interpreted.

Clarifying the interplay between humans, environment, and climate in Madagascar through time has broad implications. Today, Madagascar's environment and climate continue to change at a rapid rate. Environmental scientists and conservationists are unanimous in their dire assessments of environmental degradation and resource overexploitation by local communities and international actors (Harris *et al.* 2010; Le Manach *et al.* 2012; Rakotomanana *et al.* 2013; Seddon *et al.* 2008). It is critical that archaeologists, paleoclimatologists, and other researchers interested in the past collaborate to refine our understanding of the island's "Anthropocene" as we estimate and manage future environmental and climate change in the most resource-rich but economically impoverished nation in the Indian Ocean (Braje *et al.* 2014).

Recent Archaeological Findings

Island Colonization and Human Impact

Madagascar experienced significant climatic and environmental changes during the Holocene. Most famously, these changes have been presented as the extinction of a suite of megafauna species, the transformation and loss of primary vegetation cover over large expanses of the island and the aridification of its climate. Unfortunately, the chronological confluence of climatic and environmental changes with human colonization, the vast expanses of the island that remain archaeologically unknown (Fig. 1), and the ephemeral nature of early archaeological sites make it difficult to evaluate the manner in which humans have contributed to these changes. Although correlation does not necessarily imply causation, Madagascar has historically been burdened by its own incarnation of a “pristine myth” (Denevan 1992) of environmental catastrophe caused by human settlement (de la Bâthie 1921; Gade 1996; Humbert 1927; Klein 2002). To a limited extent, this was a reasonable premise given extreme, though equally complex, examples of island transformations elsewhere, and perhaps most famously on Rapa Nui (Flenley and King 1984; Hunt 2007; Mann *et al.* 2008; Mulrooney 2013). Fortunately, paleoecological scholarship in Madagascar is no longer constrained by colonial agendas and ample evidence has established that Madagascar’s climate and environment were not in a “pristine” and static state prior to human colonization. Instead, humans arrived on an ever-changing scene, where drivers like aridification were already redefining island ecologies (Burney 1997; Dewar and Richard 2012; De Wit 2003; Yoder and Nowak 2006).

Madagascar as an Island Laboratory

Recent human colonization followed by dramatic social, as well as environmental change are the hallmarks of many island archaeologies, with the most well-known examples coming from the Pacific (Bellwood *et al.* 1995; Kirch 2000, 2010; Lilley 2008; Steadman 2006). Islands have been described as “laboratories” or “microcosms” for research on changing climate and environment and on the impact of human colonization (Burney 1997; Florens 2013; Kirch 1997; MacArthur and Wilson 1967; Simberloff and Wilson 1969). But even in the field of island archaeology, Madagascar stands out.

The growing body of archaeological (Boivin *et al.* 2013; Dewar and Wright 1993; Mitchell 2005; Vérin and Wright 1999), historical (D’Escamps 1884; De Flacourt 2007; Grandidier 1901; Leitão 1970; Mariano 1904), linguistic (Adelaar 2010; Dahl 1977; Larson 2009; Serva *et al.* 2012), and genetic evidence (Cox *et al.* 2012; Hurles *et al.* 2005; Pierron *et al.* 2014) suggests that waves of migration from all corners of the Indian Ocean—as nearby as the African mainland and as far away as Indonesia—created Madagascar’s complex cultural geography. Each migration brought to Madagascar its own distinctive colonization package (Beaujard 2003, 2011; Blench 2007; Fuller *et al.* 2011; Kull *et al.* 2011). The island can thus be described as a laboratory where multiple colonization experiments occurred in a relatively compressed timeframe. Upon arrival, each group of settlers and the package of plants, animals, practices, and ideas they brought with them interacted with the island’s distinctive

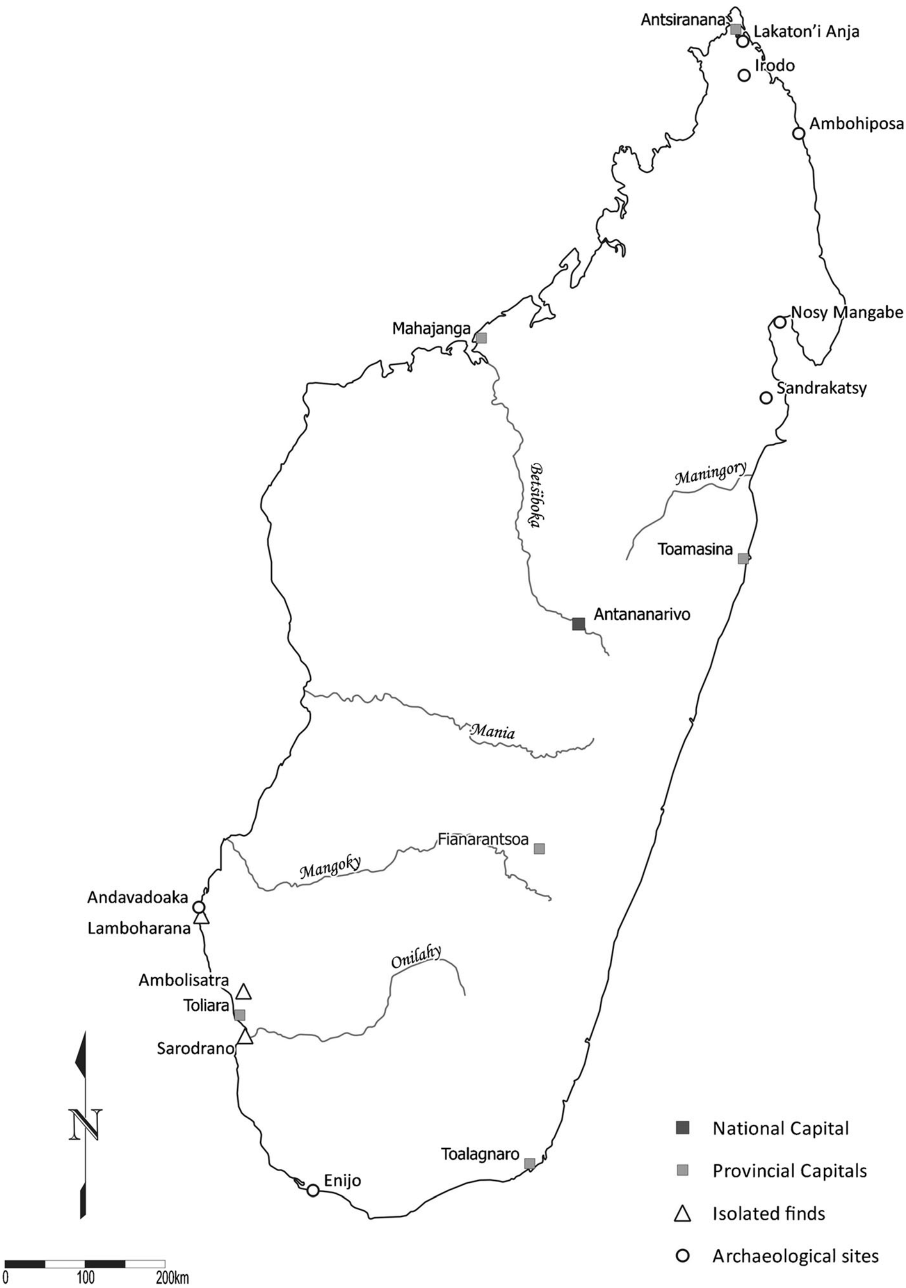

Fig. 1 Localities with well-documented archaeological sites and isolated finds dating to before AD 1000. NB: Toalagnaro is included as it is the most important city of the far south, but it is not a provincial capital (map drawn by C. Bruwer)

ecologies, topographies, and climate regimes. As a result, Madagascar offers many opportunities to study the evolution and variability of human-environment-climate dynamics, and though issues like Madagascar's megafauna extinctions have typically been situated within the debate over island colonizations, Madagascar also merits further comparison with continental extinctions of the Pleistocene (Braje and Erlandson 2013; Burney and Flannery 2006). Madagascar's very classification as an island is ambiguous (De Wit 2003), and, as has been insightfully pointed out, it need not inherit inapplicable conceptual frameworks (Dewar 1997).

New Findings from Anja

The findings from the 1980s excavations at Lakaton'i Anja, a rock shelter in the gorge of Andavakoera on the north coast of Madagascar, qualified Madagascar as the second-to-last large landmass to be colonized by humans, after New Zealand. For close to 30 years, the oldest securely dated archaeological context on the island indicated human occupation of Lakaton'i Anja (hereafter Anja) beginning from cal AD 248–570 (Dewar and Rakotovololona 1992; Dewar and Wright 1993), using the updated calibration curve for the southern hemisphere SHCal13 (Hogg 2013). Based on this date, theories of social and ecological developments in Madagascar were formulated through the lens of a compressed 1,500- to 2,000-year timeframe of human occupation of the island.

Evidence suggestive of an earlier human presence than seen at Anja had been documented in other parts of Madagascar, particularly in the south and southwest. Indicators of an earlier human arrival included faunal remains with signs of human modification (Gommery *et al*. 2011; MacPhee and Burney 1991; Perez *et al*. 2005), the first documented occurrence of nonnative species in the palynological record (Burney 1987a, b, c; Gasse and Van Campo 1998), abrupt increases in charcoal particles in sediment cores (Burney 1987b), and other indicators of human-caused disturbance (Burney *et al*. 2004). For the most part, however, this evidence was not definitively tied to contemporary archaeological contexts and in some instances presented issues with absolute dating (Battistini and Verin 1964; Crowley 2010; MacPhee and Burney 1991; Perez *et al*. 2003). Meanwhile, evidence was starting to appear for the early colonization of East Africa's offshore islands by stone-tool-using people around 2,500 cal B.C., millennia earlier than was once thought (Chami 2001).

New excavations at Anja in the past few years have yielded evidence with dramatic implications for the timing of Madagascar's initial human occupations (Dewar *et al*. 2013). Prompted by the discovery of microliths at Ambohiposa (Fig. 1), another early site on the northeast coast, the team of the Musée d'Art et d'Archéologie returned to Anja in 2011 to determine whether a similar assemblage might be present. They uncovered microlithic stone tools in deposits below what had been interpreted as sterile layers during the first excavations at the shelter. The context in which the tools were found was dated through optically stimulated luminescence (OSL) to at least 4,380 years BP±400 years, roughly 3,000 years earlier than the previously dated oldest layer at the site (Dewar and Wright 1993). These OSL results and their analysis of the microliths led the researchers to describe an early forager population on the north coast. The tools were found to share similarities with forager assemblages from East Africa, and though more evidence is needed to clarify the nature of such early settlements, the idea that Madagascar remained isolated from human action until 1,500 years ago is now untenable.

Given Madagascar's proximity to the African mainland and the patterns of island colonization in other areas like the Pacific and the Mediterranean, the evidence from

Anja supports a scenario of early long-distance migration and interaction in the WIO (Beaujard 2007). Rather than acting as a barrier, the Mozambique Channel was a corridor of interaction, linking people, plants, animals, goods, and ideas far earlier than previously thought (Boivin *et al.* 2013; Rangan *et al.* 2012). Anja's new dates present an opportunity to reexamine Madagascar's archaeological narratives and recalibrate the timeframe through which we assess social and ecological changes. Because of Madagascar's size and the relatively small contingent of archaeologists currently working on the island, it is likely that large tracts of Madagascar will remain archaeologically unexplored for some time. Nevertheless, the findings from Anja should motivate careful assessment of seemingly sterile layers, micro-screening of deposits, cleaning of residues to recover microliths, and further development of multidisciplinary strategies to interpret indicators of human action.

A Multidisciplinary Approach

Multidisciplinary collaborations between field researchers in Madagascar have been ongoing for several decades because of the apparent correlation between major changes in the island's environment and its unique and relatively recent human colonization. On such a large and biogeographically complex island, collaborative research efforts have produced important contributions, which have been carefully summarized in comprehensive reviews roughly every few years (Burney *et al.* 2004; Crowley 2010; Dewar and Richard 2012; Dewar and Wright 1993; Goodman and Benstead 2003).

Today, new archaeological findings, innovations in scientific techniques, and grim forecasts of growing poverty and rapid environmental degradation all call for a revival of this multidisciplinary tradition and for new strategies to augment the interpretive possibilities of social-ecological datasets. More work and different approaches are needed, even though teams of archaeologists, paleontologists, palynologists, and other environmental scientists have adopted a range of strategies to investigate the relationship between human arrival and dramatic changes like the extinction of the island's megafauna (Burney *et al.* 2004; Crowley 2010; Crowley *et al.* 2011; Gommery *et al.* 2003; Gommery *et al.* 2011; Goodman *et al.* 2006; Goodman *et al.* 2013; Muldoon 2010; Virah-Sawmy *et al.* 2010).

The need for innovative research is evidenced by important lacunae such as the exact timing, origins, and extent of the introduction of nonnative fauna, including ungulates (*Bos indicus*), predators (*Canis familiaris* and *Felis lybica*), and rodents (*Rattus rattus* and *Mus musculus*), capable of significantly altering native ecologies (Blench 2007; Crowley 2010; Duplantier *et al.* 2002; Fuller and Boivin 2009; Goodman *et al.* 2006; Hanotte *et al.* 2002; Hingston *et al.* 2005; Hutterer and Tranier 1990; Muldoon *et al.* 2009; Tollenaere *et al.* 2010). Though proxy indicators for the introduction of nonnative fauna have led to important insights in Madagascar and elsewhere (Davis and Shafer 2006; Wood *et al.* 2011), little direct and securely dated evidence of human-animal interaction has been documented to date. Heavy reliance on proxy indicators and the equivalent scarcity of recorded direct evidence of human-animal interaction highlight the research gap between paleontological findings and proximate archaeological contexts in Madagascar (Dewar and Richard 2012). The effort to link subfossil sites to associated archaeological contexts must be revived as a research priority (Dewar and Rakotovololona 1992), and areas with known archaeological and paleontological sites must be jointly investigated by experts representing both fields. Finally, even within disciplinary boundaries, new strategies must be applied. As a case in point, important new studies of small mammal remains from subfossil sites like Anjohibe (Fig. 4) and Ankilitelo (Fig. 6) point out that the charisma of the island's megafauna has overshadowed the importance of sampling microfauna as records of paleoenvironmental and paleoclimatic change (Crowley and Samonds 2013; Muldoon *et al.* 2009).

Challenges to Synthesizing a Narrative of Madagascar's Past

Three Problems

Madagascar's complex biological and cultural geography, variable climate regimes, and elusive early human presence pose three broad challenges to clearly distinguishing the roles of anthropogenic, environmental, and climate factors in the island's more recent transformations and to synthesizing a narrative of the island's human past. These challenges are (1) applying appropriate time scales to the interpretation of proxy indicators of human action, (2) adequately sampling the incredible diversity characteristic of the island's social-ecological systems, and (3) recognizing the ephemeral nature of forager sites and their predominance over the span of Madagascar's human history.

Time Scale

As noted earlier, proxy indicators of anthropogenic impact far outweigh direct evidence in research on Madagascar's past. While the search for direct evidence of human action continues, we must pay careful attention to the effect of applying different time scales to our interpretations of available paleoenvironmental proxies. An excellent example of the challenge of applying different time scales to evidence of environmental change comes in the form of charcoal in the sedimentary record, a well-documented proxy indicator of fire, whether caused by nature or by people (Burney 1987b, 1996; Burney *et al.* 2004). Palynology and the analysis of sediment cores from several sites in Madagascar have contributed important insights into environmental change and provide proxy indicators of human impact (Burney 1987a, b; Gasse and Van Campo 1998). Most notably, these studies have demonstrated a possible inverse correlation between the relative abundance in sedimentary layers of charcoal particles and *Sporormiella* spp., coprophilous fungi, whose abundance in sediments is an accepted signal of the presence of herbivorous megafauna (Davis and Shafer 2006). Importantly for Madagascar, where the entire Aepyornithidae family of ratites went extinct, *Sporormiella* count has also been demonstrated to indicate the presence of large avian herbivores (Wood *et al.* 2011).

Beginning in the southwest around 1720–40 years BP, a significant decrease in *Sporormiella* is followed by an increase in the amount of charcoal particles recovered. This pattern is echoed in cores taken in highland lakes several centuries later, possibly following progressive human migration from coastal areas into the highland interior (Burney *et al.* 2004; Burney *et al.* 2003). The correlation between the decrease in *Sporormiella* and the increase in charcoal densities is hypothesized to represent burning by human groups, possibly as a strategy for clearing vegetation to improve grazing for cattle and other foreign domesticates. This transformation of local ecology and increased competition among grazers may have contributed to the decline of native megafauna species and to the corresponding scarcity of *Sporormiella* in the sedimentary record. It must be noted, however, that despite the promise of correlating the relative abundance of *Sporormiella* in lake sediment cores with the presence and population densities of megafauna species, the representation of *Sporormiella* in lacustrine deposits is spatially sensitive and declines sharply with increasing distance from the dung source (Raper and Bush 2009). Other proxy indicators must be used alongside *Sporormiella* counts especially since changes in lake area and depth over time have a significant effect on the abundance of *Sporormiella* in cores and may lead to misleading spore counts (Raper and Bush 2009).

The evidence from the sedimentary record, particularly the dramatic spike in charcoal particles, is a compelling proxy for anthropogenic impact when looking through the lens of the last 2,000 years. As this was long thought to delimit human history in Madagascar, the evidence fit comfortably with a model of island colonization that sees immediate and dramatic human impact on previously isolated ecologies. If, however, the sedimentary record is viewed at the scale of the last 10,000 years, similar spikes in charcoal densities appear at more remote times for which there is no evidence of people in Madagascar. These earlier charcoal spikes suggest that the island has experienced periods of more frequent natural burning, possibly caused by climatic fluctuations (Burney *et al.* 2004; Dewar and Richard 2012). On the other hand, the occurrence of charcoal spikes during the wetter early Holocene adds an additional layer of complexity to accurately interpreting the sedimentary record in this regard (Burney 1996).

As this example demonstrates, the interpretation of paleoenvironmental proxies may be complicated by a simple shift in time scale. While a longer view of the sedimentary record in and of itself does not negate the possibility of an anthropogenic spike in charcoal around 2 kyr BP, it does call into question a model of human colonization followed immediately by significant environmental impact. Indeed, even if the spike in charcoal densities around 2 kyr BP is in fact anthropogenic, when it is viewed alongside the 4–5 kyr BP forager context from Anja, the sedimentary record testifies to a period of over 2,000 years when early populations did not manage to transform their landscape through the extensive use of fire. Though evidence of fire use by earlier foragers may exist, it clearly did not have an immediate and catastrophic effect on the island's megafauna.

Studies of Madagascar's vegetation patterns and particularly the compelling evidence for the antiquity of the island's grasslands are also pushing for a reevaluation of assumptions of widespread anthropogenic destruction of the environment (Bond *et al.* 2008; Willis *et al.* 2008). These studies underscore the importance of taking a longer view of the evolution of island ecologies, and carefully studying species diversity and niche specialization as a way to test whether certain ecological configurations are the result of recent changes that could be attributed to human arrival, or are the product of long-term evolutionary trajectories (Cristoffer and Peres 2003; Vences *et al.* 2009; Yoder and Nowak 2006).

Other studies of the response of Madagascar's floral and faunal communities to climatic shifts support a scenario in which major desiccation events were drivers of animal population declines and were augmented by the pressures of climate-stressed human populations (Virah-Sawmy *et al*. 2009, 2010). An emerging area of paleoenvironmental research that may complement or challenge existing hypotheses of anthropogenic impact is the mapping of soil bacteria communities (Blasiak *et al.* 2014). Ultimately, in order to clearly delineate human action and its links to paleoenvironmental change, scholars must continue to marshal multiple lines of proxy evidence, identify new sources of direct evidence of human action in order to mitigate the sometimes counterintuitive effect of proxies, and improve chronological control over social-ecological datasets.

Spatial Scale

The second challenge in constructing a coherent narrative of Madagascar's human past and of interactions between humans, environment, and climate lies in the island's complex biological and cultural geography. This challenge is also one of scale, as the island exhibits tremendous diversity even at highly restricted spatial scales, a situation that makes synthesis difficult and generalization impossible. In order to adequately describe Madagascar's human-environment-climate dynamics, we must continue to move away from considering the island as a monolithic unit of analysis of social-ecological trajectories.

A useful starting point for negotiating Madagascar's diversity is to subdivide the island into its various ecological zones (Fig. 2). There is significant diversity within these broadly defined ecological zones, and this kind of ecological zoning will not in and of itself ensure an adequate sampling strategy. Nevertheless, we must ensure at a minimum that we outline distinctive processes of human arrival and settlement in each major ecological zone. To date, early archaeological contexts have been identified and studied along the north, northeast, south, and southwest coasts, but large stretches of Madagascar's dry western grasslands and deciduous forests and its densely vegetated tropical east coast are sorely underrepresented in our overall sample (Fig. 1) (Dewar and Wright 1993). Improving the sample of documented archaeological sites in underrepresented areas like the east coast is important, since other fields have offered compelling arguments for the timing of human arrivals and the identities of early settlers in these areas (Serva *et al.* 2012).

In addition to improving the overall sample of early archaeological sites across all of Madagascar's broad eco-regions, we must fully leverage one of archaeology's great strengths, which is the study of past cultures through the focused lens of a localized site. Even archaeological investigations concerned with broad regional patterns are ultimately rooted in material expression at the site level. In contrast, paleoclimatology attempts to explain regional patterns within the global context of teleconnections. When paired, archaeology and paleoclimatology benefit mutually from their respective spatial expertise (Sandweiss and Kelley 2012). Given the complexity and global range of factors to consider in identifying and describing forcing mechanisms that shape individual climate records, archaeological data from a localized site offer points of intersection between paleoclimate trends and specific human trajectories (Gunn and Folan 2000). In turn, archaeology reveals scenarios of human action and material expression that can be more richly interpreted if contextualized by paleoclimate findings. The approach therefore should be to build up the database of localized archaeological data, by

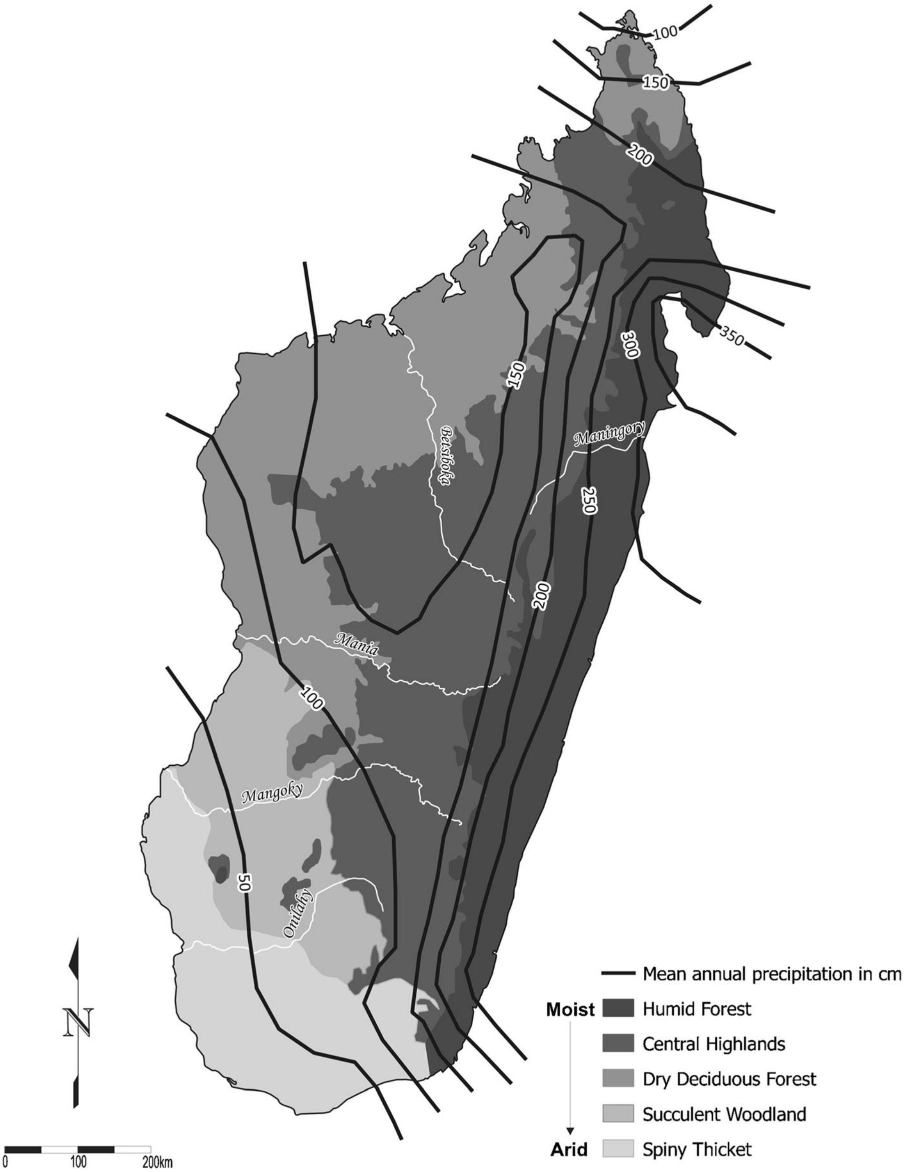

Fig. 2 Madagascar's macro ecological zones as defined by an east-west precipitation gradient (adapted from Crowley 2010; map drawn by C. Bruwer)

endeavoring to represent more of Madagascar's cultural and biogeographic diversity and consistently interpreting archaeological data jointly with well-resolved regional paleoclimate records. Though the individual site has been emphasized here as a unit of analysis for paleoclimate reconstruction, this is in no way meant to diminish the importance of regional survey as an essential methodological approach in Madagascar where early forager sites are difficult to detect and present a range of taphonomic challenges.

Ultimately, the traditional questions surrounding the human colonization of Madagascar—namely its timing and the identities of early settlers—must continue to be research priorities, but they must also be reformulated to reflect the distinctive trajectories of colonization and human-environment-climate coevolution at the scale of individual social-ecological contexts. To treat Madagascar as a monolithic stage on which a single colonization play unfolds is unproductive, and doing so, perhaps even unconsciously, has led to an acknowledged lack of consensus on Madagascar's colonization narrative. Indeed, Madagascar presents multiple narratives of colonization throughout its human history, each of which provides a unique opportunity to explore the "entangled" relationship between humans, their environment, and climate through time (Hodder 2012).

Borrowing the phrase "entangled" from Ian Hodder's discussion of the relationships between humans and things serves merely to underscore the progressively complex nature and consequences of these relationships. It also urges us to consider nonlinear models in describing how humans, the environment, and climate interact. Though a linear approach has been used to parse the consequences of human arrival on island ecologies (Burney 1997), linearity also constrains our ability to assess dynamic reciprocal exchanges. Therefore, it is important to identify all of the ways in which "entanglements" manifest themselves in social, ecological, and climatological change at the more resolved scale of individual social-ecological contexts.

Ephemeral Forager Sites

Though it calls for revision of models of social, environmental, and climate change, the discovery of the early forager occupation layer at Anja adds to Madagascar's importance in the study of island colonizations. The earliest date from Anja more than doubles the period of interaction between Madagascar's human and natural communities and opens the possibility for slower rates of environmental change. Madagascar thus emerges as an even more remarkable example of island colonization since most other well-studied examples see drastic changes to island ecologies in the centuries following human arrival (Burney and Flannery 2005). The settlement of Madagascar at a remote period by forager populations, followed much later by the arrival of herders and farmers who may have linguistically and genetically "masked" the presence of early foragers (Pierron *et al*. 2014), should also encourage more comparison of Madagascar with islands of the Caribbean that experienced a similar colonization process (Rodriguez Ramos 2010).

Based on Anja's unique status in Madagascar archaeology as the only site thus far documented that dates to such a remote period, it appears that ephemeral forager sites that can be difficult to detect could characterize at least three quarters of Madagascar's archaeological record. The difficulty in detecting ephemeral forager sites and, as the situation at Anja indicates, the low density of artifacts we can expect to find both present the third major challenge to understanding human-environment-climate dynamics in Madagascar, and specifically anthropogenic contributions to major changes such as the extinction of all animals over 10 kg in weight (Burney *et al*. 2004; Crowley 2010).

First, there is little conscious expression through material culture of the relationship between forager groups and their environment in Madagascar, at least not that has been documented thus far. Attention to rock art in Madagascar is increasing (Middleton 2013, 2010; Radimilahy 2010), and emerging research on the rock art of southwestern Madagascar (Rasolondrainy 2011) should contribute important insights into forager engagement with broad landscapes, as similar research has done in other parts of the world (Balme *et al.* 2009; Garfinkel *et al.* 2010; Williams *et al.* 2010).

Second, when it appears that for the majority of Madagascar's human history that small populations of foragers were engaging with the island's environment, it is hard to attribute significant changes like mass extinctions exclusively to human action. Taking the megafauna extinctions as an example, even if documented population increases and growth in the number and size of sedentary villages between AD 700–1000 (Dewar and Wright 1993; Parker Pearson 2010; Rakotoarisoa 1998; Vérin 1986) put additional pressure on habitats and transformed vegetation patterns (Reyes 1993), no data thus far collected testify to intensive hunting of megafauna species. Though the ongoing analysis of faunal remains from Anja may offer evidence of intensive hunting of lemur species (Henry Wright, personal communication), the hitherto reported hippo and lemur bones with cut marks are only indicative of occasional hunting (Gommery *et al.* 2011; MacPhee and Burney 1991; Perez *et al.* 2005).

Aside from the evidence for intensive human exploitation of Madagascar's large extinct mammals, archaeological investigations in the southwest are accumulating evidence of human interaction with the island's Aepyornithidae ratites. These extinct giant flightless birds included several taxa, the largest of which is estimated to have weighed as much as a ton and truly merits the popular name "elephant bird." In-progress analysis of ratite eggshell from forager sites near the modern village of Andavadoaka is revealing direct evidence of exploitation of eggs by foragers, allowing a new basis for inferences about the impact of egg harvesting on ratite extirpation (Douglass in prep.). As eggshell fragments are a far more prevalent find than elephant bird bones in Madagascar, their intensive study is key to elucidating elephant bird phylogeny, ecology, and extinction trajectories (Clarke *et al.* 2006; Goodman and Jungers 2013; Goodman *et al.* 2013). Moreover, the archaeological investigations in Andavadoaka have yielded the first documented ratite eggshell beads recovered in Madagascar to date along with other worked pieces of ratite eggshell that offer new opportunities to interpret the relationships between forager groups and their environment.

Nevertheless, without evidence of megafauna kill sites, as seen in places like New Zealand that also suffered mass extinctions post-human arrival (Anderson 1989) or data on the health of megafauna populations on the eve of human arrival (Allentoft *et al.* 2014), it is difficult to make the case for purely human-driven extinctions following a "blitzkrieg" model of intensive hunting (Flannery 1990; Martin 1984). There is growing consensus that the megafauna extinctions in Madagascar were "protracted" in time, "mosaic-like" in space, and propelled by a synergistic combination of anthropogenic and climate factors (Burney 1999; Burney *et al.* 2004; Crowley 2010; Crowley *et al.* 2011; Virah-Sawmy *et al.* 2010). Still, we must bring new evidence to bear that reconciles the roughly 4,000-year period during which small forager populations were the only human communities in Madagascar, with the relatively recent final occurrences of megafauna species (Crowley *et al.* 2011; Goodman *et al.* 2013; Virah-Sawmy *et al.* 2010). In order to do so, we must more carefully examine the interplay between foragers and the environment and climate of Madagascar by cross-referencing paleoclimatic, paleoenvironmental, and archaeological datasets and by targeting "integrated sites" where multiple datasets from contemporary strata can be compared (Burney 1999).

Archaeology and Paleoclimate Reconstruction

Combining Archaeology and Paleoclimatology

When paleoclimate and archaeological research intersect, emphasis is often placed on understanding the response of human communities to the advantages or stresses imposed by climatic conditions. This research trend was recently described in detail in an important review of the reciprocal contributions of archaeology and paleoclimatology to the major questions of these two fields (Sandweiss and Kelley 2012). Archaeological studies encompassing a range of geographies and theoretical perspectives have demonstrated significant correlations between climate fluctuations and the full range of human action, thought, and material expression from population movements and shifting settlement patterns (Cremaschi and Lernia 1999; Huffman 2008; Grosjean *et al*. 2005; Maldonado *et al*. 2010; Schild and Wendorf 2001; Williams *et al*. 2010) to subsistence strategies, conflict, and religious and political trajectories (Clark and Reepmeyer 2012; O'Connor and Kiker 2004; Prasad *et al*. 2014; Winsborough *et al*. 2012). Without this research and its multidisciplinary methodological innovations, our understanding of major anthropological questions would be severely limited. But to focus exclusively on the effects of climate on human life is to partially observe a dynamic and complex interplay in which humans can be immensely agentive (Alley *et al*. 2003; Cooper and Sheets 2012; Funk 2014; McIntosh *et al*. 2000; Rosen 2007; Sandweiss and Kelley 2012). This seems like an obvious statement in the post-"Inconvenient Truth" era (Gore 2006). Nonetheless, the dominant archaeological paradigm has been that climate impacts human cultures, and we must often turn to other disciplines for discourse on the reverse flow of the human-climate exchange and for more holistic conceptual frameworks that account for the complex feedback mechanisms at play in social-ecological systems (Berkes and Folke 2002; Bird *et al*. 2013; Braje *et al*. 2014; Gelorini and Verschuren 2013; Von Heland and Folke 2014). While archaeological discourse on the human-environment relationship is open to the potential of humans and their environment to influence one another, climate is viewed more as causation than effect and is often presented as disastrous, inexorable, and sudden (Diamond 2011; McAnany and Yoffee 2009; Tainter 2006).

In Madagascar, little archaeological evidence of past anthropogenic climate-forcing has been documented, though studies of modern-day dynamics clearly demonstrate the impact human action can have on climate change (Grove *et al*. 2013a, b; Maina *et al*. 2012; Maina *et al*. 2013). In studies of the past, the primary effort has been to distinguish anthropogenic and climate factors that may have contributed to environmental change (Virah-Sawmy *et al*. 2010). Though it is easier said than done, we must strike a balance between efforts to separate anthropogenic and climate factors—efforts which are propelled by a desire to settle on a coherent post-colonization narrative for Madagascar—and a holistic understanding of the reciprocal relationships between humans, environment, and climate throughout the island's history. In order to strike this balance, we must continually address the challenges described above. First, more data must be collected from early archaeological sites for comparison with the findings from Anja so that indicators of human disturbance can be contextualized chronologically. Second, we must increase the sample and representation of sites across Madagascar's diverse ecological zones so that varied post-colonization trajectories may be explored. Finally, we must develop strategies to glean evidence about forager engagements with island landscapes from ephemeral, low-artifact-density sites and carefully assess lithic technologies that have only recently been identified and connected to early forager groups (Dewar *et al.* 2013) so that we can better understand how dramatic changes like the megafauna extinctions occurred on an island with a long "forager phase" and no documented evidence of mass kill-sites.

A predominance of ephemeral forager sites throughout much of Madagascar's archaeological sequence may ultimately make it difficult to achieve a high-resolution view of human-environment-climate interaction until later periods. Nevertheless, successful work to elucidate forager-climate interaction elsewhere—albeit in places with a much longer archaeological record—confirms the valuable insights to be gained from this avenue of research (Williams *et al.* 2010). Securely dated cultural occupation layers in Madagascar should therefore be evaluated to see if relevant paleoenvironmental indicators can be compared to the growing body of well-resolved paleoclimate sequences in the WIO (De Boer *et al.* 2014; Grove *et al.* 2013a, b; Prasad *et al.* 2014; Zinke *et al.* 2009). We advocate the systematic cross-referencing of paleoclimate indicators from archaeological and paleontological sites with the existing well-resolved regional climate records of the WIO as a productive methodological approach. The combination of archaeological and paleoclimate data creates a necessary system of checks and balances (Gunn and Folan 2000).

Coastal archaeological sites are especially valuable in offering checks and balances for regional paleoclimate records, as coastal settlements generally yield remains of both marine and terrestrial organisms that can be analyzed for paleoclimate reconstruction. The value of comparing marine and terrestrial data for paleoclimate reconstruction in the Indian Ocean has already been well-established by paleoclimatologists (De Boer *et al.* 2014; Rijsdijk *et al.* 2011; Zinke *et al.* 2009; Zinke *et al.* 2014a, b). Indeed, given the tremendous influence of ocean systems in shaping global climate patterns, it is essential to systematically investigate land-sea interrelations (Gunn and Folan 2000; Zinke *et al.* 2009). Indian Ocean dynamics, in particular, are highly complex and present many challenges for comprehensive reconstruction of regional climate histories (Zinke *et al.* 2009; Zinke *et al.* 2014a, b). The southwest coast of Madagascar presents an especially good opportunity to explore land-sea connections because of the rich archaeological and paleontological remains that can be used to ground-truth regional climate records.

Madagascar's Dominant Climate Mechanisms

Madagascar's climate history is complex, and a comprehensive review is not attempted here. The following section aims to provide a brief overview of the dominant climate mechanisms that shape the island's climate. Madagascar has experienced many different climate regimes since it started the process of becoming an island around 135 million years ago (Yoder and Nowak 2006). The most extreme changes in the island's climate are due to its radically different positioning relative to 30° latitude over geological time (Fig. 3). As it began to separate from Africa and then from India, Madagascar's landmass drifted southeast until the entirety of the island was situated below 30° latitude. This position enveloped Madagascar in arid subtropical conditions, with the implication that all of its plant and animal life would have been adapted to a desert environment (Wells 2003).

As the landmasses that once formed Gondwana drifted further apart, Madagascar's overall climatic situation continued to fluctuate. Between 60 and 35 million years ago, the island began drifting back north, until it reached its present location well north of 30° south latitude in the tropics, where the majority of the island now lies (Dewar and Richard 2012). It is therefore clear that Madagascar's plant and animal life has, over the course of geological time, weathered many extreme shifts in climatic conditions (Wells 2003). The environment and climate of Madagascar were never static and were certainly in flux at the time of human arrival during the middle-to-late Holocene. Comparable scenarios can be seen in other parts of the world (*e.g.*, Brenner *et al.* 2002).

The varied topography of Madagascar plays an important role in shaping the island's distinct climate and ecological zones, particularly with regard to variability in rainfall (Fig. 2). The island is broadly characterized by an east-to-west rainfall gradient (Dewar and Richard 2007). Heavy rainfall along the east coast results in dense tropical ecologies and is bounded from north to south by the high eastern edge of the highlands. From the highlands heading west, mean annual precipitation drops sharply, with the west and particularly the southwest experiencing severe aridity.

Madagascar's current position in the Indian Ocean makes it susceptible to a variety of important forcing mechanisms. With the exception of the far south, the island lies in the southern tropics and is influenced by the Southwest Indian Ocean monsoon system. The austral summer from December to March brings the heaviest rains, with lighter

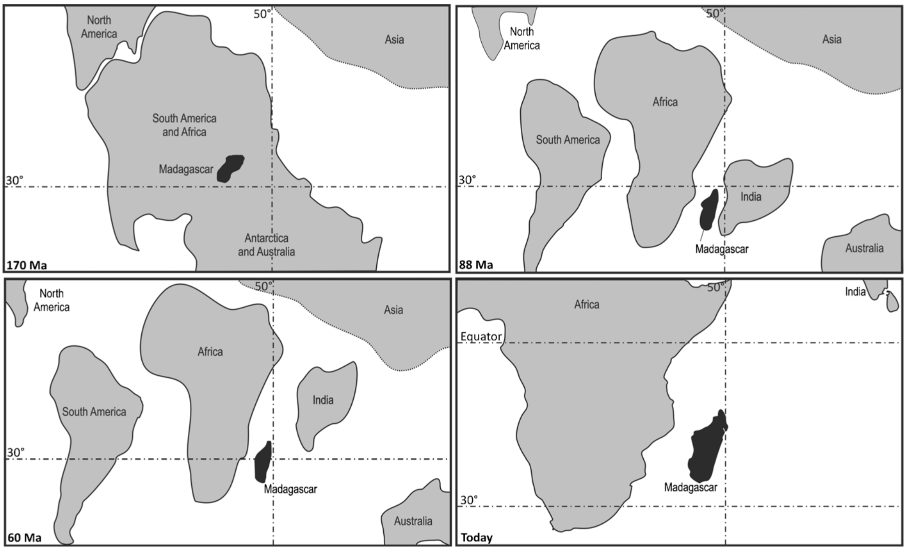

Fig. 3 Madagascar's relative position over geological time (adapted from Yoder and Nowak 2006; map drawn by C. Bruwer)

rains from October to December (Jury 2003). Monsoon precipitation is carried to Madagascar by the southeast trade winds, which are in turn modulated by the seasonal north-south shifting of the Inter-Tropical Convergence Zone (ITCZ). Madagascar's rainfall patterns show high variability in time and space, with important implications for the evolution of island biota and human subsistence practices (Dewar and Richard 2007).

Variations in Indian Ocean sea surface temperatures (SSTs) also influence rainfall patterns (Grove *et al.* 2013a, b; Tierney *et al.* 2008; Tierney *et al.* 2011; Zinke *et al.* 2009). An important area of current climate research is in describing the effect of far-reaching oscillations in SSTs like the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) on Western Indian Ocean nations (Crueger *et al.* 2008; Grove *et al.* 2013a, b; Tierney *et al.* 2011). In modern times, there is growing evidence for the influence of ENSO on Madagascar's rainfall patterns and on the frequency and intensity of cyclones (Mavume and Rydberg 2009; Zinke *et al.* 2004; Zinke *et al.* 2009).

Finally, deep ocean currents like the strong Agulhas current also play an important role, as they influence SSTs, precipitation, and the availability of marine resources (Bard and Rickaby 2009; Zinke *et al.* 2004; Zinke *et al.* 2014a, b). Through a process of upwelling, these currents and large ocean eddies bring to the surface cold, nutrient-rich water that lowers SSTs and influences coastal ecologies (Beal *et al.* 2011; Peeters *et al.* 2004). More work is needed to clarify the influence of the Agulhas current on Madagascar's climate (Beal *et al.* 2011).

Early and Middle Holocene Records

Though the mechanisms that shape climate throughout the tropics are complex and not fully understood, climate records from the WIO are contributing important insights into the evolution of climate worldwide (Burns *et al.* 2003; Dixit *et al.* 2014; Piotrowski *et al.* 2009). Notably, WIO climate records spanning the end of the Pleistocene provide data that are germane to debates over the differential manifestations of the Younger Dryas (YD) in the Northern and Southern Hemispheres and the transition in Africa to a wetter early Holocene (Talbot *et al.* 2007; Tierney *et al.* 2008; Tierney *et al.* 2010; Tierney *et al.* 2011). Indeed, data indicate that the climate fluctuations that characterize the end of the YD in the Southern Hemisphere are primarily hydrological, whereas the Northern Hemisphere experienced extreme shifts in surface air temperatures (SATs) (Talbot *et al.* 2007).

The transition to the early Holocene and the ensuing wetter conditions has been an important research focus for understanding social and environmental trajectories around the Indian Ocean rim (Prasad *et al.* 2014; Preston and Parker 2013). Several studies of Holocene climate records from the WIO indicate successive wet and dry phases that can be compared for a more comprehensive understanding of regional trends in the variability of rainfall (Crowley and Samonds 2013; De Boer *et al.* 2014; Fleitmann *et al.* 2007; Gasse and Van Campo 1998; Van Rampelbergh *et al.* 2013). In fact, because of its implications for the lifeways of the island's human and natural communities, the availability and variability of rainfall is arguably the central focus of paleoclimatological reconstruction for Madagascar's Holocene (Dewar and Richard 2007).

In Madagascar, the climate records spanning the late Pleistocene and Holocene come from speleothems at Anjohibe Cave in the northwest (Brook *et al*. 1999; Wang and Brook 2013) and lake sediment cores from the north, central highlands, and southwest (Fig. 4). Lake sediment cores from the north come from Lakes Ampasambazimba and Alaotra in the north and northeast (Reyes 1993) and from Lake Mitsinjo in the northwest (Matsumoto and Burney 1994). Samples from the central highlands come from Lakes Tritrivakely (Burney 1987a, b, c; Gasse and Van Campo 1998), Matsabory Ampozolana (Burney 1987b), Miangola (Burney 1987b), and Kavitaha (Reyes 1993). Finally, the southwest is represented by studies of Lake Ihotry (Vallet-Coulomb *et al*. 2006). The archives from all of the abovementioned lakes testify to a dry late Pleistocene when natural fires and savannah vegetation were common (Burney 1987b; Gasse and Van Campo 1998; Reyes 1993). The longest continuous archive comes from Lake Tritrivakely. Coring yielded a 40,000-year-long sediment core, which revealed extreme hydrological fluctuations in the Pleistocene (Gasse and Van Campo 1998) and episodes of increased burning during the Holocene, including during the wetter early Holocene (Burney 1987a, b, c).

The Holocene climate archive from Anjohibe Cave in northwest Madagascar was recently bolstered by a 2-m-long stalagmite that has provided the longest continuous speleothem record from Anjohibe and indicates a wet early and middle Holocene, with two major desiccation events at 7.5 and 4 kyr BP, after which point a general drying is observed (Wang and Brook 2013). The speleothem record from Anjohibe and studies of the surrounding vegetation histories offer great potential to better understand Holocene rainfall patterns (Burney *et al*. 1997; Crowley and Samonds 2013; Wang and Brook 2013). The fluctuations at Anjohibe are broadly echoed by the shorter

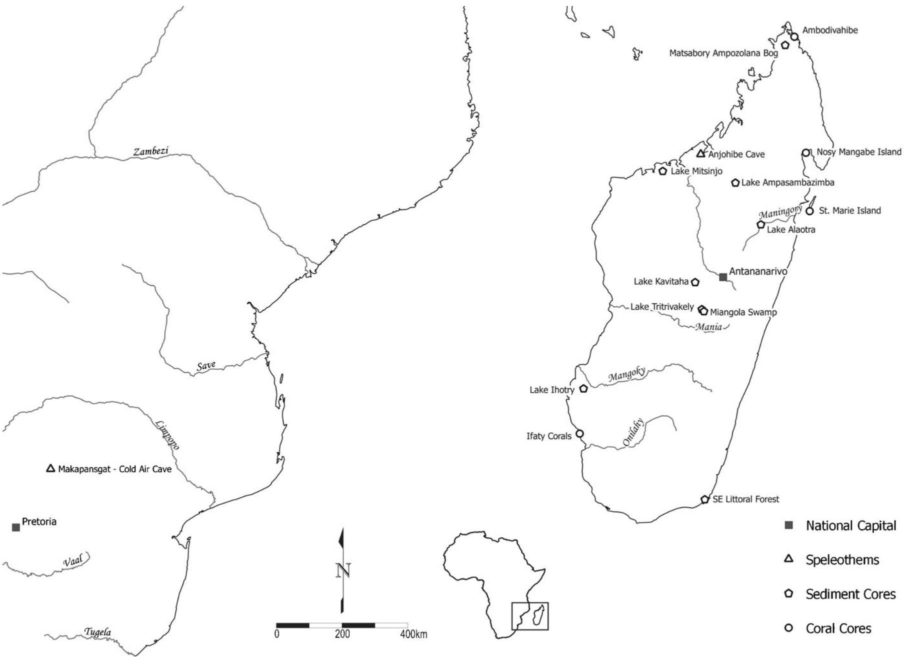

Fig. 4 Locations of regional climate archives (map drawn by C. Bruwer)

sedimentary record from Lake Ihotry, where a wet episode is noted from *ca*. 3–2 kyr BP (Vallet-Coulomb *et al*. 2006). Though higher spatial and temporal resolution is needed, the climate archives from across Madagascar suggest that mid-Holocene desiccation events cascaded across Madagascar from north to south starting around 4 kyr BP at Anjohibe Cave in the far north, and reaching the southwest at Lake Ihotry around 2.5 kyr BP (Burney 1987b; Matsumoto and Burney 1994; Reyes 1993; Vallet-Coulomb *et al*. 2006; Van Campo *et al*. 2007; Wang and Brook 2013).

Lastly, it is important to consider that the WIO region has experienced significant changes in sea level throughout the Holocene (Camoin *et al*. 2004; Zinke *et al*. 2003). Sea-level change is a parameter that must not be neglected, as it carries important implications for coastal communities and ecologies (Saleem Khan *et al*. 2012; Sales 2009; Virah-Sawmy *et al*. 2009; Woodroffe and Murray-Wallace 2012). Cores sampled from the microcontinental margins of Madagascar, the granitic Seychelles and volcanic Réunion, Mauritius, and Comoros reveal a range of tectonic responses to late glacial to postglacial melting of large ice sheets, and confirm the link between deglaciation events and ocean volumes (Camoin *et al*. 2004). In the case of Madagascar, the island's heavy continental shelf creates high vertical responses to postglacial melt water. Starting between 1.5 and 2 m below present-day, sea level begins to rise around 5 kyr BP. At 2.5 kyr BP, sea level peaks approximately 2 m higher than today, followed by a steady decline from 2.5 kyr BP to present levels (Camoin *et al*. 2004). Sea-level rise combined with other climate drivers has already been linked to threshold events for Madagascar's coastal ecologies (Virah-Sawmy *et al*. 2009), and the impact of sea-level rise must be carefully considered in understanding the responses, adaptations, and resilience of coastal communities—both human and natural—in the past and present (Hughes *et al*. 2005).

Coral Records and the Modern Phase

Despite the insights derived from Tritrivakely, Anjohibe, and Ihotry, the size and biogeographic diversity of Madagascar necessitate improved spatial and temporal resolution of climate records, especially with regard to SATs and rainfall patterns. Though shorter in their temporal span, oxygen isotope records obtained from coring of Indian Ocean corals provide the most detailed archives of regional climate change (Zinke *et al*. 2009). Long-lived *Porites* spp. corals have been cored near the Seychelles, Kenya, Mayotte, Madagascar, and La Réunion (Fig. 5). To date, four locations in Madagascar have been successfully cored (Fig. 4): Ambodivahibe (Jens Zinke, personal communication), Nosy Mangabe (Grove *et al*. 2013b), St. Marie (Grove *et al*. 2013a), and Ifaty (Zinke *et al*. 2004). Of the samples from these locations, the core from Ifaty reef in southwest Madagascar yielded the most well-resolved oxygen isotope time series, extending back 336 years with bimonthly resolution (1659–1920) and monthly resolution (1920–1995) that reflect changes in SSTs on a decadal time scale with a frequency range of 16–18 years (Zinke *et al*. 2004; Zinke *et al*. 2009).

The Ifaty core closely correlates with climate patterns of the southern Mozambique Channel and Agulhas current region. Comparisons of the oxygen isotope time series from the Ifaty core with the Makapansgat speleothem record from Cold Air Cave (CAC) in South Africa show close affinity between the two records. Warm SST anomalies recorded by the corals correspond closely with increased rainfall over central and eastern Africa, suggesting that the higher and more widely agreed-upon resolution

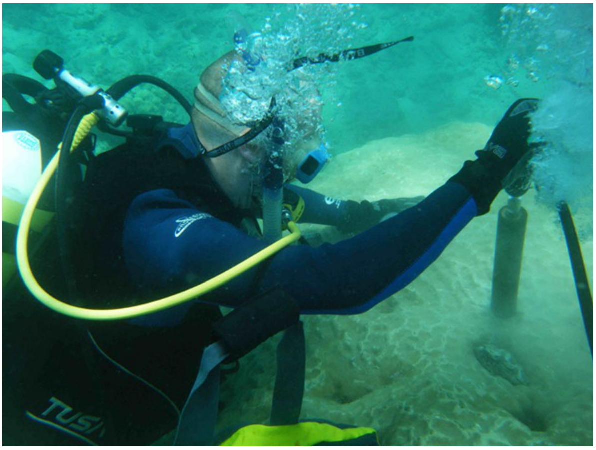

Fig. 5 J. Zinke coring a massive *Porites* sp. coral in Antongil Bay, Madagascar in 2008 (photo: C. A. Grove)

provided by the corals can be used to clarify issues with other regional records (Sundqvist *et al*. 2013; Zinke *et al*. 2009). The Makapansgat record, though covering a longer time period than the Ifaty corals, has generated some disagreements in its interpretation and suitability for describing Southern African rainfall trends (Huffman 2008; Stager *et al*. 2013). While samples from other corals throughout the WIO and especially Madagascar would further improve resolution (Lough 2004), the demonstrated reliability of the Ifaty record and its agreement with regional records, such as the Makapansgat archive, give confidence that similar interrelations between WIO SSTs and rainfall can be inferred for more remote Holocene times (Grove *et al*. 2013a, b; Zinke *et al*. 2009).

Finally, strong inferences about the influence of ENSO in the WIO prior to instrumental records remain difficult, but the demonstrated positive correlation between higher WIO SSTs and increased rainfall support observations about the reach of ENSO and the effect of global warming in the WIO in recent times (Crueger *et al*. 2008; Grove *et al*. 2013a, b; Hoerling *et al*. 2006; Zinke *et al*. 2004; Zinke *et al*. 2009). Furthermore, multiple proxy indicators from the Mauritian lowlands suggest that increasing influence of ENSO variability in the WIO is linked to anomalously negative phases (lower SSTs) of the Indian Ocean dipole (IOD) (De Boer *et al*. 2014). A better understanding of ENSO influence in the WIO is critical to estimating the impact of global warming on an increase in the frequency and intensity of cyclones in the region (Mavume and Rydberg 2009).

Potential for Research Collaboration in Southwest Madagascar

Southwest Madagascar is the most arid region of the island and receives on average less than 50 cm of rainfall per year (Fig. 2). The region's biota is highly endemic and varies according to the underlying geology (Du Puy and Moat 2003). Broadly speaking, the coastal strip of the southwest features Quaternary dune systems characterized by the xerophytic and picturesque spiny thicket biome. The spiny thicket boasts the highest levels of floral endemicity of the island with unique species of *Euphorbia* and families like the Didiereaceae being entirely endemic to the region (Gautier and Goodman

2003). As one heads east into the interior, the unconsolidated sands give way to Tertiary limestone, with Mesozoic limestone outcrops in the northern part of the southwest (Du Puy and Moat 2003). These formations are covered by a mosaic of dry deciduous forests and savannah grasslands (Gautier and Goodman 2003). The high biodiversity of the terrestrial biomes of the southwest is matched by rich, though critically endangered, marine life, including mangrove forests and some of the island's healthiest coral reef systems (Gabrié *et al.* 2000; Harris *et al.* 2010; Nadon *et al.* 2007).

In the previous sections, the Ifaty coral core and the Lake Ihotry sediment core were briefly discussed. Both of these records come from southwest Madagascar, and they represent respectively marine and terrestrial contexts. Despite political difficulties in Madagascar over the last decade, field research in the southwest has continued to extend our understanding of the region's social-ecologies, both past and present. Indeed, the southwest boasts active or recently completed research projects spanning the related fields of archaeology (Andavadoaka, Lamboharana, Belo-Sur-Mer), paleoclimatology (Ifaty corals, Lake Ihotry), paleontology (Anakao, Ankilitelo), and ecology and evolutionary biology (Andavadoaka, Beza Mahafaly) (Fig. 6). Several of these active projects have collected, or have the potential to collect, contemporary indicators of paleoclimate and paleoenvironment that can be compared through multidisciplinary collaborations. Cross-referencing these datasets will offer opportunities to put social-ecological data from specific localities into the broader context provided by regional paleoclimate records like the Ifaty oxygen isotope time series and answer more sophisticated questions about past interactions between humans, environment, and climate.

Fig. 6 Active archaeological, paleoclimatological, paleontological, and ecological research projects in southwest Madagascar with potential for collaborations for the study of social-ecological systems in the past and in the present (map drawn by C. Bruwer)

By way of an example of the potential for multidisciplinary collaboration, we propose a case study of combining isotopic measurements from marine and terrestrial sources from securely dated archaeological contexts around Andavadoaka (Figs. 1 and 6) with the oxygen isotope time series obtained from the Ifaty reef. The climate archive of the coral core will be interpreted alongside oxygen and carbon isotope ratios of contemporary ratite eggshell and marine shell from the sequence of archaeological deposits, in order to evaluate the applicability of cross-referencing these marine and terrestrial datasets for paleoclimate reconstruction. We also encourage the search for fossil corals to reconstruct the nearshore marine climate of southwest Madagascar on seasonal time scales, to have a more direct overlap with archaeological sites (Fig. 7). Fossil corals dating back to 4–5 kyr BP should be located near the SW and W offshore islands and within the Ifaty-Toliara reef systems. By combining these data, the foodways and settlement sequence of Andavadoaka will be viewed against a backdrop of changing SSTs and variation in effective moisture, which may lead to a better understanding of seasonality and resource exploitation among forager groups. Furthermore, many archaeological sites near Andavadoaka have yielded abundant remains of extinct ratite eggshell, some of which is associated with a context dated at the earliest to cal AD 1663. Pending further chronometric analysis, these ratite remains currently represent the latest absolutely dated occurrence of the giant flightless birds in Madagascar. The fact that some of them show clear signs of human modification makes their thorough analysis and comparison with paleoclimate records essential in reconstructing human-fauna interaction.

Conclusion

This paper has presented Madagascar as a unique place to study human-environment-climate dynamics because of the island's complex, and in many ways bewildering, natural and culture history. This case has been made before, however, and others have provided far more comprehensive reviews of scholarship to date (Dewar and Richard 2012). Here, we hope to have extended the conversation given the new and dramatic

Fig. 7 Coring of fossil corals in Mauritius in 2010 (photo: C. A. Grove)

findings from Anja that push back the date of human occupation of Madagascar to between 4 and 5 kyr BP. Moreover, we aimed to promote the southwest of Madagascar as an auspicious region for research collaboration given the timely convergence of several active research projects, on land and on sea. These projects span multiple disciplines including archaeology, paleoclimatology, paleontology, and even modern conservation science.

Clearly, more work is yet to be done, and this paper has merely highlighted some of the considerations and possibilities for future research into Madagascar's past. At a minimum, the new findings from Anja call for a revision of a model of Madagascar's initial human colonization followed immediately by catastrophic degradation of the island's ecologies. As more evidence emerges, we must set aside a single linear narrative of pre- and post-human-arrival Madagascar and envisage multiple colonization "experiments," even within restricted localities. We will likely find that some scenarios of human-environment-climate interaction indeed led to decreased biomass and biodiversity within island ecologies. But, we may also be surprised by other scenarios in which human groups engineered and engaged with landscapes sustainably and in ways that increased biodiversity (Balée 1998; Brookfield and Padoch 1994; Jones *et al*. 1996; McNeil *et al*. 2010; Peters 2000; Von Heland and Folke 2014). The extinction of Madagascar's megafauna will continue to attract the spotlight, particularly as more public attention is focused on extinctions today (Braje and Erlandson 2013; Kolbert 2014). This provides all the more reason to carefully assess direct evidence of human-fauna relationships in the past, so as not to construct inaccurate and politicized narratives of the negative impact of impoverished local communities on Madagascar's environment (Fox 2000; Kull 2002; Pollini 2010).

Archaeologists, paleoclimatologists, and other experts on the past can lend long-term perspectives on social, environmental, and climate change to the formulation of development and conservation policy. This is especially important in African contexts, as there is an increasingly alarmist—and historically rooted (McCann 1999)—trend in the literature to describe an exceptional vulnerability of African landscapes and populations to climate change and environmental degradation (Fraser *et al*. 2013; O'Connor and Kiker 2004; Paavola 2008; Schilling *et al*. 2012). While poverty increases a population's vulnerability to environmental degradation and stress (S. Hughes *et al*. 2012), alarmist "disaster and collapse" models can stand in stark contrast to longer-term perspectives on the foodways and subsistence practices of African populations (Cinner *et al*. 2013; Logan 2012). Such perspectives must come from the careful integration of archaeological, paleoclimatological, and paleoenvironmental research and from broad dissemination of multidisciplinary findings. Better integration of these fields and of their respective methodologies and datasets will lead to more meaningful results and expand the possibilities for these findings to be applied to resolving modern-day challenges (Bodin and Tengö 2012; Caseldine and Turney 2010; Davies 2012; Gunn and Folan 2000).

Today, Madagascar continues to undergo rapid environmental change, and its population is frequently confronted with climatic extremes, as in 2012 when much of the island was devastated by cyclone Giovanna, one of the most destructive cyclones to hit Madagascar on record. Madagascar is undoubtedly one of the most resource-rich nations in the Indian Ocean, but it is also one of the poorest. Its position in a fast-developing macro-region, with countries like India and China leading the development race, puts incredible pressures on Madagascar, its population, and its natural resources. The island's serious development and conservation concerns add urgency to the need for more integrated research into the interdependent trajectories of its people, environment, and climate (Bruggemann *et al.* 2012; Gelorini and Verschuren 2013; Maina *et al.* 2013; Tadross 2008). We must continually review our understanding of the significant changes this island has experienced as new archaeological, paleoenvironmental, and paleoclimatological findings become available, if our findings are to have any relevance to the construction of a more sustainable future.

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