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Radiocarbon evidence for the presence of mice on Madeira Island (North Atlantic) one millennium ago

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Owing to the catastrophic extinction events that occurred following the Holocene arrival of alien species, extant oceanic island biotas are a mixture of recently incorporated alien fauna and remnants of the original fauna. Knowledge of the Late Quaternary pristine island faunas and a reliable chronology of the earliest presence of alien species on each archipelago are critical in understanding the magnitude and tempo of Quaternary island extinctions. Until now, two successive waves of human arrivals have been identified in the North Atlantic Macaronesian archipelagos (Azores, Madeira, Selvagens, Canary and Cape Verde Islands): 'aboriginal', which is limited to the Canary Islands around two millennia ago, and 'colonial', from the fourteenth century onwards. New surveys in Ponta de São Lourenço (Madeira Island) have allowed us to obtain and date ancient bones of mice. The date obtained (1033 $\pm$ 28 BP) documents the earliest evidence for the presence of mice on the island. This date extends the time frame in which the most significant ecological changes occurred on the island. It also suggests that humans could have reached Madeira before 1036 cal AD, around four centuries before Portugal officially took possession of the island.

1. Introduction

Oceanic islands provide important insights for the study of evolution. Owing to the fact that catastrophic extinction events occurred everywhere following the Holocene arrival of alien species, extant island biotas are a mixture of the recently incorporated alien fauna and the remnants of the original fauna. Evolution and extinction have been intensively studied in island vertebrates [1–3]. The North Atlantic Macaronesian archipelagos (i.e. Azores, Madeira, Selvagens, Canary and Cape Verde Islands; figure 1), with different numbers of islands, geological ages, distances to the mainland and timing of human arrival, are ideal territories for the study of such processes. The knowledge of both Late Quaternary pristine island faunas and a reliable chronology of the early presence of aliens on each archipelago are critical to understanding the magnitude and tempo of Quaternary island extinctions.

Accelerator mass spectrometry (AMS) radiocarbon dating on commensal rodents has been widely used as a powerful tool to establish accurate chronologies for the early human presence on islands [4,5]. Until now, two successive waves of human colonization have been identified in Macaronesia: 'aboriginal' and 'colonial'. In Macaronesia, only the Canary Islands harboured 'aboriginal' populations. AMS ^{14}C dating on introduced house mouse *Mus musculus domesticus* [6], and on endemic fauna of sites without it, indicates that humans reached this archipelago sometime between 756 cal BC and 313 cal AD [7]. On the other hand, the 'colonial' colonization wave affected all the Macaronesian archipelagos and took place from the fourteenth century onwards.

Current data indicate major extinction events in the Macaronesian islands subsequent to human arrivals. Among Upper Pleistocene–Holocene original

Figure 1. Location of the Macaronesian archipelagos. The fossil site where the bones of mice were collected is indicated on Madeira Island (red arrow). (Online version in colour.)

faunas of the Canary Islands, two genera and three species of endemic rodents, one species of giant lizard and at least seven species of endemic birds (two shearwaters, one quail, one oystercatcher, one bunting and two finches) and five species of non-endemic birds are now extinct. Chronological data indicate that all these species became extinct after human arrival [8–13]. A recent and impressive loss of endemic species seems to have occurred in the Madeira archipelago [14]. In this small archipelago, with only two main islands (Madeira and Porto Santo) and without terrestrial native mammals (excluding bats), bones obtained from Holocene dune fossil sites indicate that at least two-thirds of the endemic birds (three species of rail, two quails, one scops owl, one thrush and one finch), plus two non-endemic species became extinct [14,15]. In electronic supplementary material, table S1, we present the list of the extinct birds and mammals from the Macaronesian archipelagos.

According to historical data, in the year 1419 the Portuguese took possession of Madeira, and the island was subsequently populated. It is usually assumed that, very probably, the Madeiran extinctions took place within the past 600 years. On Madeira, two different lines of evidence point to the presence of mice previous to the Portuguese colonization: (i) the finding of four subfossil bones of mice *Mus*

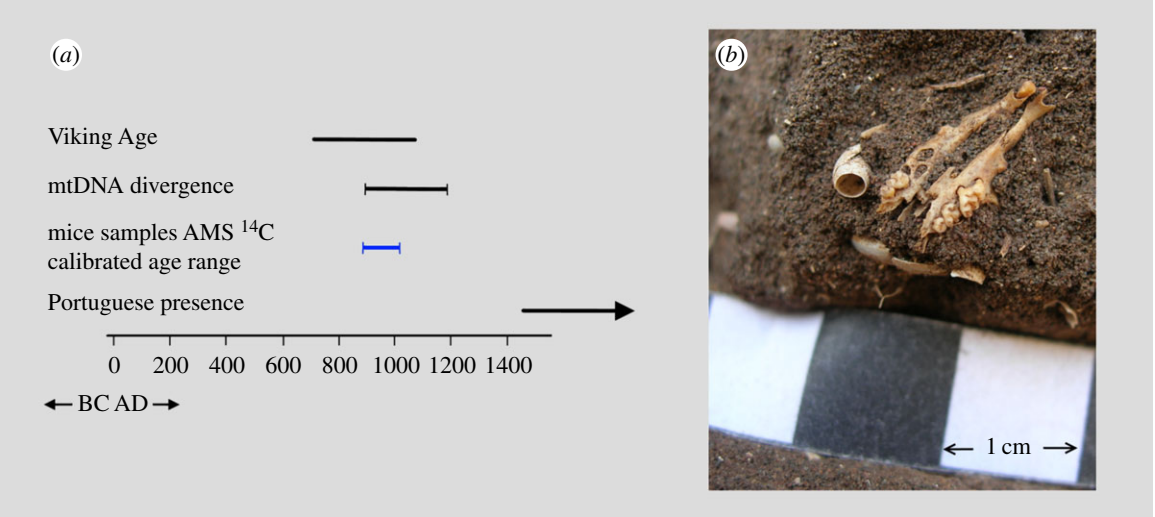

Figure 2. (*a*) Radiocarbon calibrated age range for the ancient mice from Madeira (upper and lower limits of 2σ confidence interval), Viking Age [22], proposed colonization time interval from mitochondrial D-loop sequences of current house mouse population of Madeira [23], and the date for Portuguese presence on the island. (*b*) Skull of ancient mouse (ventral view) in Ponta de São Lourenço (Madeira Island). (Online version in colour.)

musculus s.l. in a dune deposit [16], although the lack of radiocarbon dating on these materials did not allow us to confirm an age prior to the fifteenth century; (ii) the mtDNA haplotypes from current populations of house mouse *M. m. domesticus* of Madeira, which show similarities with those of Scandinavia and northern Germany (but not with the Portuguese mainland). This second line of evidence suggests that northern Europe was the source area, and raises the intriguing possibility that the Vikings could have brought the house mouse to the island [17], although it should be noted that to date there are no historical references of Viking voyages to Macaronesia.

The house mouse *M. musculus* spread from southeast Asia through Eurasia with human migrations during the Holocene. Two subspecies are currently present in Europe: the Western house mouse *M. m. domesticus*, in the Mediterranean and Western Europe; and the Eastern house mouse *M. m. musculus*, in Central and Eastern Europe [18]. The expansion of the Western house mouse in the Mediterranean began in the Eastern basin around the eighth millennium BC. It colonized the Western Mediterranean and northern Europe during the first millennium BC [19]. The Western house mouse was well settled on the Northeast coast of Spain in the second half of the first millennium BC [20]. The Eastern house mouse has been present in Eastern Europe at least since the fourth millennium BC [21].

The aim of this paper is to provide the first AMS ^{14}C date of ancient mouse bones from Madeira, and to point out the possible consequences of this new date.

2. Material and methods

(a) New ancient samples of mouse bones

The new surveys on Madeira have provided two small samples of mouse bones from a dune site in Ponta de São Lourenço (red arrow in figure 1). In May 2010, a first sample (a single right mandible of 0.04 g) was collected. In November of 2011, at the same place, a second sample was collected. It included a fragmented skull (figure 2*b*), two fragmented jaws, three tibia, one complete femur, one fragmented femur, two fragmented humeri, two fragmented pelvises, three isolated incisors and one caudal vertebra (total weight = 0.42 g). Other taxa present at this site are shearwaters (*Puffinus* sp.), petrels (*Pterodroma* sp.), pigeons (*Columba* sp.), an undescribed species of quail (*Coturnix*), the Madeiran scops owl (*Otus mauli*), the barn owl (*Tyto alba*) and several undescribed species of passerines (at least *Turdidae* and *Fringillidae*) [14,15].

(b) Radiometric dating and isotopic methods

Samples were dated through AMS at the Radiocarbon Accelerator Unit of the University of Oxford. AMS determinations were made on extracts of ultrafiltered bone gelatin [24]. Additionally, a fragment of barn owl humerus and three bones (a complete femur and tibiotarsus and a fragmented tarsometatarsus) of a new, still undescribed, species of quail from the same locality were AMS dated using an improved collagen extraction [25] by modified Longin method [26] at the Koninklijk Instituut voor Het Kunstpatrimonium (Brussels). No difficulties in obtaining the ^{14}C date were reported from either laboratory.

Isotope ratio for C are presented as δ values, where $\delta = 1000[(R_{sample}/R_{standard}) - 1]$, and $R = {}^{13}C/{}^{12}C$. The isotopic reference standard is Vienna–PeeDee Belemnite.

(c) Conventions used for radiometric ages

The AMS radiocarbon dates given in years BP are conventional radiocarbon ages with standard error, where BP is before present (the year 1950), following standard reporting procedures. Radiocarbon calibration was calculated using the software OxCal v. 4.2 [27] and the IntCal13 dataset [28]. Dates calculated from calibration are expressed as 2σ intervals (95.4% confidence) and given as 'cal AD' or 'cal BC', AD being, *Annus Domini* and BC, *Before Christ*.

3. Results

Owing to their fragmentary condition and to the absence of any other rodent of Quaternary age in the island, we have cautiously attributed these new mouse bones to *M. musculus s.l.*

The first sample submitted for AMS-dating turned out to be too small to furnish a ^{14}C age. The second sample (Lab-Code: OxA-26216) delivered the earliest testimony of the presence of mice on the island known so far: 1033 ± 28 BP, with a 2σ confidence interval of 903–1036 cal AD (figure 2*a*). A barn owl bone from the same site offers a similar

age (Lab-Code KIA-48920: 1060 ± 30 BP; 897–1024 cal AD), whereas a quail turned out to be older (Lab-Code KIA-47430: 2755 ± 55 BP; 1021–806 cal BC).

The $\delta^{13}C$ value for the dated mouse sample (−17.66‰) falls within the range of the two bones of terrestrial birds from the same site (−15.53‰ for the barn owl and −18.6‰ for the quail), and within the range of dated rodent samples from the Canary Islands obtained at several sites located far inland from the shore (−16.99 to −20.12‰ for house mouse and −15.98 to −18.62‰ for lava mouse *Malpaisomys insularis* in the Canary Islands) [7]. Samples of animals with a marine diet (i.e. shearwaters) from the Canary Islands display higher $\delta^{13}C$ values (−11.51 to −13.61‰) [12,13]. See list of $\delta^{13}C$ data of Holocene bird and mammal bones from the Macaronesian islands in the electronic supplementary material, table S2.

Our data indicate that it is highly unlikely that the mouse bones from Madeira that have been dated reflect a marine component in the diet. It is consequently improbable that the calibrated age of this sample was affected by the ^{14}C marine reservoir effect.

4. Conclusion

Although a natural colonization by mice–via natural rafts, like those suggested for the presence of endemic rodents on the Canary Islands, which are located around 100 km from the African coast [29]–cannot be totally excluded, it appears to be highly improbable. It should be mentioned here that the Western Mediterranean islands, despite being closer to the mainland than Madeira, were not colonized by mice until the commercial and demographic spread of Phoenicians and Greeks during the last millennium BC [30]. Also, because of the island's isolation, it is highly unlikely that the ancient mouse sample reached Madeira transported by a bird (i.e. inside a pellet).

If we assume that humans transported mice to Madeira, the new date presented herein suggests that humans could have reached the island before 1036 cal AD, thus around four centuries before Portugal officially took possession of the island. The 2σ confidence interval of OxA-26216 (900–1036 cal AD) falls within Viking Age (eighth to eleventh centuries) [22], and agrees with one of the two proposed colonization time intervals obtained from mitochondrial D-loop sequences of current house mouse populations of Madeira (the mismatch distribution of pairwise genetic differences approach: 910–1185 AD) [23]. mtDNA haplotypes from current mouse populations of Madeira show similarities with those of Scandinavia and northern Germany [17], and it has been reported that Vikings transported house mice to the places they reached [31,32]. All these data suggest, but do not prove, a relationship between the Viking voyages and the presence of *Mus* on Madeira.

Once settled, the mouse population could have reached very high densities owing to its high reproductive potential, particularly in the absence of rats (*Rattus* spp.), which limit their number. In this case, a wide range of native biota could have been impacted, and the magnitude of the impact could have been huge, as occurred on islands without rats [33,34]. Nevertheless, more radiocarbon, genetic and morphometric data [6,19–21] are necessary to establish the precise evolutionary history of mice on Madeira (including the subspecific diagnosis of the ancient mice), the precise extent of the impact of the arrival of mouse on the island, and the causes and precise chronologies of bird extinctions on Madeira. The new date provided herein demonstrates the early presence of mice on Madeira and provides a longer time span in which the most severe ecological changes during the Late Holocene occurred on the island after the arrival of mice (i.e. at least *ca* one millennium ago).

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