

Pollen, phytoliths, arthropods and high-resolution ^{14}C sampling from Rano Kau, Easter Island: evidence for late Quaternary environments, ant (Formicidae) distributions and human activity

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Abstract A 20-m sediment core from Rano Kau, Easter Island provides plant microfossil, arthropod fossil and high-resolution ^{14}C sampling evidence for late Quaternary environments, ant (Formicidae) distributions and human activity. The record commences prior to or during the LGM, providing the two oldest dates for Rano Kau thus far, $20,340 \pm 160$ and $34,260 \pm 440$ BP. The vegetation at the time was

mostly *Arecaceae* (palm)-dominated grassland-woodland, suggesting cooler/drier conditions than present. Near the start of the Holocene *c.* 12,500 cal BP, climate alleviation is indicated by *Asteraceae* shrubland increasing at the expense of grassland. There is an early to mid-Holocene sediment hiatus. The record recommences *c.* 3,500 cal BP, with in-washed clayey soils bearing charcoal and phytoliths of Polynesian-introduced *Musa* (banana) and mixed with wetland detritus, reflecting slumping as a result of forest clearance and gardening. Dates of material of other plants from the clay/detritus layers containing the *Musa* phytoliths are

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older than expected, within the range 3,680–2,750 cal BP, well before settlement of Eastern Polynesia. This could reflect horticultural material settling in an older part of the sediment column or age increase by reservoir effects. A long section of overlying unconsolidated detritus provides a progressively younger upward sequence from 2,840–2,870 to 930–810 cal BP, but dates are variable after 1,290–1,180 cal BP, where charcoal, disturbance-related pollen and older than expected ant exoskeletons demonstrate the inclusion of pre-aged material from the floating vegetation mat or upslope erosion in the sediment column. Arecaceae pollen declines sharply after 930–810 cal BP. Arthropod analysis reveals two new weevil species for Easter Island, and two ant taxa, *Tetramorium bicarinatum* and *Pheidole* sp., the latter of which is also new for the island. Three of the four age determinations on ant remains suggest that ants were present prior to *c.* 2,500 cal BP, and probably associated with the period following the resumption of sediment accumulation *c.* 3,500 cal BP. Unless the apparent ant ^{14}C ages have been increased by reservoir effects, these results question the long-accepted assumption that all Eastern Polynesia's ant species have been introduced.

Keywords ^{14}C · Pollen · Phytoliths · Arthropods · Ants · Agriculture · Easter Island

Introduction

Easter Island (Rapa Nui) is well placed for the study of past human impact on physical environments. It is extremely isolated, with a typically fragile island ecosystem, and was settled relatively late in human migration therefore evidence has not been obliterated by lengthy occupational activity. A long-held theory, partly based on ample evidence for biotic extinctions, is that depletion of the island's resources caused a prehistoric ecological collapse, including large-scale human population decline (Diamond 2005). This has recently been challenged, however, with some researchers suggesting European effects, particularly disease, as the main cause of the population decline (Hunt and Lipo 2006). Many of the Rapa Nui environmental reconstructions are based on proxy evidence, mostly pollen, from the island's three main wetlands, in the volcanic craters at Rano Kau, Rano Raraku and Rano Aroi (Fig. 1).

Sediment cores from the Rapa Nui wetlands have provided environmental records for the last *c.* 35,000 years. Initial pollen cores showed that the island formerly had extensive Arecaceae-dominated forest (Flenley et al. 1991). The climate appeared cooler and drier than present during 26,000–12,000 BP. Holocene trends included progressive replacement of forest largely by grassland after human arrival. Subsequent pollen and other paleoenvironmental studies from these wetlands support these findings, but establishing reliable chronologies has been hampered by unconformities, inversions, long age plateaux, hiatuses and older than expected dates (Dumont et al. 1998; Butler and Flenley 2001; Peteet et al. 2003; Azizi and Flenley 2008; Mann et al. 2008; Sáez et al. 2009; Butler and Flenley 2010; Cañellas-Boltà et al. 2012; Horrocks et al. 2012a, b).

A recent development has been the discovery of introduced crop microfossils in sediment cores from Rapa Nui, providing unequivocal evidence of human presence (Horrocks et al. 2012a, b). Rano Kau wetland is particularly promising for providing advances in the island's paleoenvironmental research because it is large, virtually its entire surface is accessible by foot, and it has thick deposits allowing fine resolution sampling. Studies of this wetland do not extend beyond *c.* 13,000 BP (Gossen 2007), however, and tend to show a high rate of both age inversions and older than expected dates. We aim to extend the Rano Kau vegetation-climate record well beyond the Holocene, integrate evidence of human activity into a longer-term context and improve the chronology. As well as plant microfossil data, we also present results of analysis of fossil arthropods, accompanied by high-resolution ^{14}C sampling.

Study area

Rapa Nui is an isolated island in southeast Polynesia (27°09'S, 109°26'W). The timing of Polynesian settlement is uncertain. Using fossil pollen evidence of forest disturbance, Butler and Flenley (2010) suggested human activity as early as *c.* 1,900 BP. Using radiocarbon evidence from archaeological excavations, many researchers agreed on a settlement date of a little before 1,100 BP (Steadman 1995; Green 2000; Martinsson-Wallin and Crockford 2001), but this has recently been challenged. Based

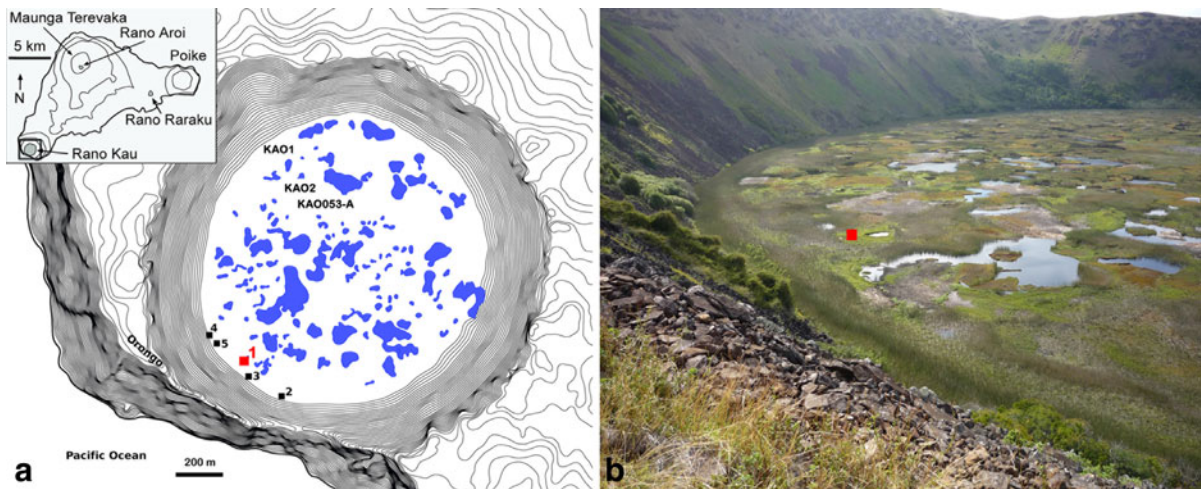


Fig. 1 **a** Rano Kau, showing core site locations (inset: Rapa Nui). 1: this study; 2–5: Horrocks et al. (2012a); KAO1, 2: Flenley et al. (1991), Butler et al. (2004), Butler and Flenley (2001, 2010); KAO053-A: Gossen (2007). **b** West side of Rano Kau 2009, looking north, showing core site, 53 m from lake

on an archaeological excavation and reassessment of previous radiocarbon dates from the island, Hunt and Lipo (2006) suggested a later date for colonisation, 800 BP. On a wider Pacific Island scale, based on an archaeological excavation in Mangareva, Kirch et al. (2010) suggested that Polynesians expanded rapidly through the chain of islands extending from the southern Cooks through at least some of the Australs, to Mangareva, the Pitcairn-Henderson group, and to Rapa Nui, *c.* AD 1,000. Based on a meta-analysis of 1,434 ^{14}C dates from the region, Wilmschurst et al. (2011) argued that reliable samples showed a dual phase settlement of Eastern Polynesia: earliest in the Society Islands *c.* AD 1,025–1,120, then dispersal continued in one major pulse to all remaining islands, including Rapa Nui, *c.* AD 1,190–1,290.

Our coring site is the circular crater lake (110 m altitude) of Rano Kau (324 m altitude) (Fig. 1). The site has been described previously (Ferdon 1961a; Flenley et al. 1991). The inner walls are ~125 m high and steep, $>30^\circ$. The lake is ~1.25 km wide. The lake surface is mostly covered by ~1–3 m deep floating mats of vegetation, with pockets of open water. The water gaps between the floating mats and the underlying sediment surface are up to 10.5 m. The upper third of the interior walls of the crater are typically basalt cliffs, with the lower two-thirds comprising loose boulder talus.

edge. For approximate scale, the lake is ~1.25 km wide and the narrow, dark green belt of *Scirpus* fringing the lake is up to 2 + m high. Much of the lake vegetation is disconnected from the sediment column, as floating mats

Several sediment core studies from Rano Kau have previously been carried out, details of which are given elsewhere (Flenley et al. 1991; Butler and Flenley 2001; Butler et al. 2004; Gossen 2007; Butler and Flenley 2010; Horrocks et al. 2012a) (Fig. 1). Ferdon (1961b, c) and McCoy (1976) recorded a heavy concentration of archaeological sites in and around Rano Kau. The commonest feature within the crater was terracing, thought to be for gardens and dwellings. The relict village of Orongo, on the western crater rim, comprises ~50 stone houses. A recent study of ^{14}C age determinations of charcoal thought to be associated with people in soils around Orongo showed age ranges up to *c.* 730 cal BP (Mann et al. 2008). Our immediate sampling site in the crater is in the southwest part of the lake, ~800 m from the previous coring in the northwest part, and ~20–30 m out from the previous coring below Orongo village.

Materials and methods

A 20-m sediment core (1) was taken through the floating mat vegetation 53 m from the southwest edge of Rano Kau lake (UTM easting/northing GPS coordinates: 669647 6998960), using D-section and Livingstone corers (Fig. 1). Coring ceased when deposits became too compacted to continue.

Magnetic susceptibility was recorded to identify mineral layers using cross-calibrated Geoinstruments JH-8 and Bartington MS2E1 devices. Values are plotted in SI units on \log_{10} scale.

The core was analysed for pollen, phytoliths, starch and arthropods. Pollen and insects were analysed to the full depth of the core. An initial examination of a few samples showed that phytoliths were present only in the clay/detritus layers, and that starch separations of the detritus deposits yielded very high concentrations of wetland plant material and no convincing starch evidence. For these reasons, further starch analysis was discontinued and phytolith preparations were confined to the part of the core encompassing the clay/detritus layers and a few samples from the detritus deposits immediately above.

Samples were prepared for pollen analysis by the standard acetylation method (Moore et al. 1991). The pollen sum for most samples was at least 200, excluding ‘Wetland taxa’ and ‘Ferns and others’. Tablets containing a known quantity of exotic *Lycopodium* spores were added to pollen samples to allow charcoal concentrations to be calculated. As a 130 μm sieve was used for pollen preparation, charcoal $>130 \mu\text{m}$ was excluded. Samples were prepared for phytolith and starch analysis by density separation (Horrocks 2005). The phytolith sum was at least 200, excluding Cyperaceae. Samples were prepared for arthropod analysis by washing through a 300 μm sieve. In several sections of the core, remains of two ant species were identified. As these are thought to be introduced, thus providing important evidence of human presence, additional material from around the deepest remains, encompassing 10.95–11.05 m depth, was examined.

^{14}C age determinations were carried out by the Rafter Radiocarbon Laboratory, Lower Hutt, New Zealand using EN-Tandem or extended NEC compact AMS (Baisden et al. 2012), except for the ant exoskeletons, which required alternative methods (Santos et al. 2007) due to their small size (20–50 μg C) (Table 1, Fig. 2). For most of the samples, tiny ($\leq 1.5 \text{ mm}$) fruits/seeds, often fragmented, of *Scirpus* and other plants were used for dating. Remaining samples comprised plant shoot material and ant remains. Calibrations were performed using the SHCal04 (Reimer et al. 2004). Ant and floating vegetation mat results presented in Fig. 2 were prepared in OxCal v4.1, and the Bayesian age-depth model was prepared in Bacon (Blaauw and Christen

2011) with 10 cm increments, an accumulation rate prior of 0.5 cm year^{-1} based on the assumption of stable accumulation from 15 to 7 m depth, and a ‘memory’ prior of 0.5 suggesting moderate link between accumulation rate in any layer to the previous layer. For Fig. 2, the minimum error applied to calibrations was 30 years, reflecting the performance of secondary standards and wider tails on distributions.

Results

Lithostratigraphy, radiocarbon and magnetic susceptibility

The lowermost deposit in the Rano Kau core, from 20 to 18 m depth, is compacted detritus, finer than the detritus layers above (Figs. 3, 4). ‘Detritus’, throughout this paper, refers to organic material originating from wetland/lake vegetation. Dates from the base, middle and near the top of this layer are $20,340 \pm 160 \text{ BP}$, $34,260 \pm 440 \text{ BP}$ and 13,214–12,110 cal BP respectively, showing an inversion (Table 1). Overlying the compacted detritus to 17.2 m depth is a clay and detritus layer, which returned two dates collectively between 3,684 and 2,861 cal BP. A layer of fine detritus lies above this to 16.15 m depth, with four dates collectively between 3,476 and 3,003 cal BP and slightly inverted. There is another clay/detritus layer above this to 15.75 m depth, with two dates collectively between 3,058 and 2,753 cal BP.

Unconsolidated coarse detritus with several water gaps overlies the upper clay/detritus layer to 1 m below the surface (Figs. 3, 4). The gap depths are as 7.18–5.00 m, 4.69–4.00 m and 2.18–2.08 m. The coarse detritus is dated near the base, at 15.6 m depth, to 2,843–2,720 cal BP (Table 1). Another 13 dates above this, encompassing a long section of the core to 4.8 m depth, progressively decrease to 930–811 cal BP, except for a short section within this from 11.1 to 10.4 m depth which has inversions. Three dates of ant remains in this section have 95 % confidence intervals ranging from c. 1,600–5,000 cal BP. A further eight dates from after 4 m depth to 1.2 m depth also show inversions including another ant date of c. 3,900–2,900 cal BP at 2.6 m depth. Living rhizomes cap the deposits.

Information from the stratigraphy was used to construct an age-depth model (Fig. 2) for the period of

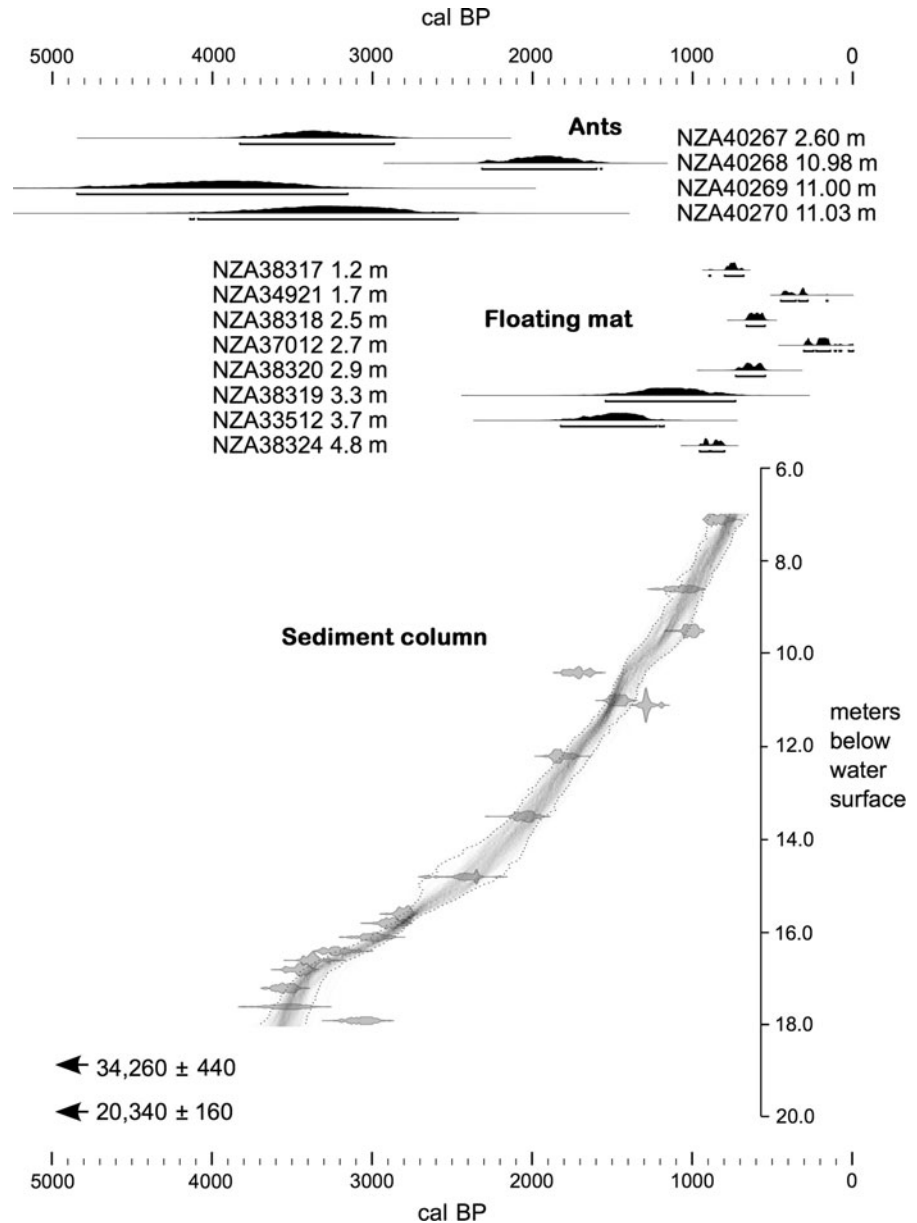
Table 1 AMS radiocarbon dates from Rano Kau core 1 (McCormac et al. 2004; Reimer et al. 2004)

| Depth (m) | Material (*fruits/seeds) | NZA | ¹⁴ C BP | Cal BP (2σ) | δ ¹³ C (‰) ([†] assumed) |
|------------|---|-------|--------------------|---------------|--|
| 1.2 | 6 undif.* | 38317 | 890 ± 10 | 958–567 | –28.7 |
| 1.7 | 1 <i>Scirpus</i> , 5 undif.* | 34921 | 309 ± 15 | 438–296 | –26.3 |
| 2.5 | 4 undif. shoot | 38318 | 674 ± 45 | 661–549 | –28.0 |
| 2.6 | 1 <i>Tetramorium</i> head, 1 abdominal segment | 40267 | 3,204 ± 193 | 3,902–2,925 | –29.2 |
| 2.7 | 4 <i>Scirpus</i> *; 1 undif. shoot | 37012 | 220 ± 25 | 302–142 | –25.7 |
| 2.9 | 5 undif.*, 1 undif. shoot | 38320 | 727 ± 70 | 728–548 | –26.6 |
| 3.3 | 3 undif. shoot | 38319 | 1,280 ± 210 | 1,525–738 | –28.8 |
| 3.7 | 4 <i>Scirpus</i> , 7 undif.* | 33512 | 1,620 ± 150 | 1,867–1,284 | –24.5 |
| 4.8 | 1 <i>Scirpus</i> , 7 undif.* | 38324 | 1,029 ± 15 | 930–811 | –22.7 |
| 7.1 | 2 <i>Scirpus</i> * | 37011 | 918 ± 25 | 899–729 | –24.8 |
| 8.6 | 1 undif. shoot | 34920 | 1,147 ± 25 | 1,059–956 | –25.0 [†] |
| 9.5 | 1 <i>Scirpus</i> , 1 undif.*; 6 undif. shoot | 38325 | 1,106 ± 15 | 1,044–928 | –26.8 |
| 10.4 | 5 <i>Scirpus</i> , 1 undif. Cyperaceae* | 37003 | 1,788 ± 25 | 1,710–1,560 | –24.4 |
| 10.95–11.0 | 1 <i>Tetramorium</i> head, 3 abdominal segments | 40268 | 2,028 ± 149 | 2,345–1,628 | –21.7 |
| 11.0 | 1 <i>Pheidole</i> head | 40269 | 3,657 ± 325 | 4,957–3,211 | –32.4 |
| 11.0 | 2 <i>Scirpus</i> * | 38879 | 1,578 ± 20 | 1,516–1,345 | –24.7 |
| 11.0–11.05 | 1 <i>Tetramorium</i> head | 40270 | 3,131 ± 319 | 4,238–2,504 | –28.1 |
| 11.1 | 3 <i>Scirpus</i> , 3 undif.* | 38326 | 1,361 ± 15 | 1,289–1,179 | –24.8 |
| 12.2 | 6 <i>Scirpus</i> , 22 undif.*; 1 undif. shoot | 34914 | 1,886 ± 30 | 1,886–1,638 | –25.0 |
| 13.5 | 1 undif. shoot | 37004 | 2,071 ± 25 | 2,046–1,885 | –27.9 |
| 14.8 | 1 <i>Scirpus</i> , 1 undif.* | 33261 | 2,361 ± 40 | 2,454–2,153 | –24.8 |
| 15.6 | 7 <i>Scirpus</i> * | 37260 | 2,697 ± 35 | 2,843–2,720 | –27.1 |
| 15.8 | 6 <i>Scirpus</i> * | 37261 | 2,785 ± 35 | 2,921–2,753 | –28.7 |
| 16.1 | 13 <i>Scirpus</i> * | 37262 | 2,869 ± 35 | 3,058–2,792 | –28.3 |
| 16.4 | 5 <i>Scirpus</i> * | 37013 | 3,017 ± 25 | 3,241–3,003 | –28.4 |
| 16.6 | 10 <i>Scirpus</i> , 10 undif.* | 33680 | 3,150 ± 30 | 3,444–3,332 | –25.9 |
| 16.8 | 7 <i>Scirpus</i> , 1 undif. Cyperaceae* | 37007 | 3,235 ± 35 | 3,476–3,272 | –27.9 |
| 17.2 | 6 <i>Scirpus</i> * | 37263 | 3,322 ± 35 | 3,579–3,389 | –27.2 |
| 17.6 | 2 <i>Scirpus</i> , 7 undif.* | 33259 | 3,297 ± 80 | 3,684–3,267 | –27.8 |
| 17.9 | 12 <i>Scirpus</i> * | 37264 | 2,916 ± 35 | 3,138–2,861 | –28.6 |
| 18.2 | 2 <i>Scirpus</i> , 5 undif.* | 33260 | 10,830 ± 240 | 13,214–12,110 | –27.3 |
| 19.1 | Bulk sediment | 34986 | 34,260 ± 440 | N/A | –25.4 |
| 20.0 | 2 undif.* | 32805 | 20,340 ± 160 | N/A | –19.9 |

plausibly continuous deposition between the resumption of accumulation at 18 m depth and the sediment surface at 7 m depth. In Fig. 2, dates obtained below the 18 m hiatus are shown for comparison, as are dates obtained on ant exoskeletons and within the floating vegetation mat. A plausible age-depth model was constructed with variable deposition rates. Variability in dates increased at approximately 11.1 m depth, although dating is sparse between 11.1 and 16 m depth, making the exact location where variability increases

difficult to ascertain. This variability could be explained by the corer dragging down older material, or mixing within the sediment column, but seems most likely to be associated with the emergence of the floating mat. The variable dates obtained within the floating mat suggest that sloughing and deposition of variably aged material in the sediment column is a plausible explanation for variable dates. Magnetic susceptibility is shown on the pollen diagram lithostratigraphic column (Figs. 3, 4). This analysis confirms the presence of mineral layers,

Fig. 2 Radiocarbon calibrations from Rano Kau (Table 1). The age-depth relationship estimated by the Bacon model is shown for the depth range starting at the top of the sediment column, at 7 m depth, to the apparent hiatus, at 18 m depth. Calibrations obtained for the floating mat and ant exoskeletons are shown separately for comparison, and dates obtained below the apparent hiatus at 18 m are also indicated. The bars underneath calibrations, and the dotted line surrounding the Bacon probability density shading indicate 2σ confidence intervals



with peak values at 17.96, 17.1 and 15.9 m depths. The ^{14}C results in the 15.9–18.0 m zone suggest that the deposition of these mineral layers did not cause variability or inversions in the age-depth model shown in Fig. 2, although one sample at 17.9 m depth did give an anomalously young date.

Pollen

The lowermost two samples of Rano Kau core 1, from the compacted fine detritus layer commencing

at 20 m depth, are dominated by *Arecaceae* and *Poaceae* pollen (Figs. 3, 4). Small amounts of pollen of *Asteraceae*, *Coprosma*, *Sophora*, *Triumfetta* and *Urticaceae/Moraceae* and of spores of foveolate *Lycopodium* also feature. Subsequent samples in this layer show major increases in *Asteraceae* pollen and foveolate *Lycopodium* spores, and a coincident decrease in *Poaceae* pollen. Wetland taxa are barely represented in the compacted fine detritus layer. *Asteraceae* pollen and *Lycopodium* spores all but disappear in the sample immediately above this, as

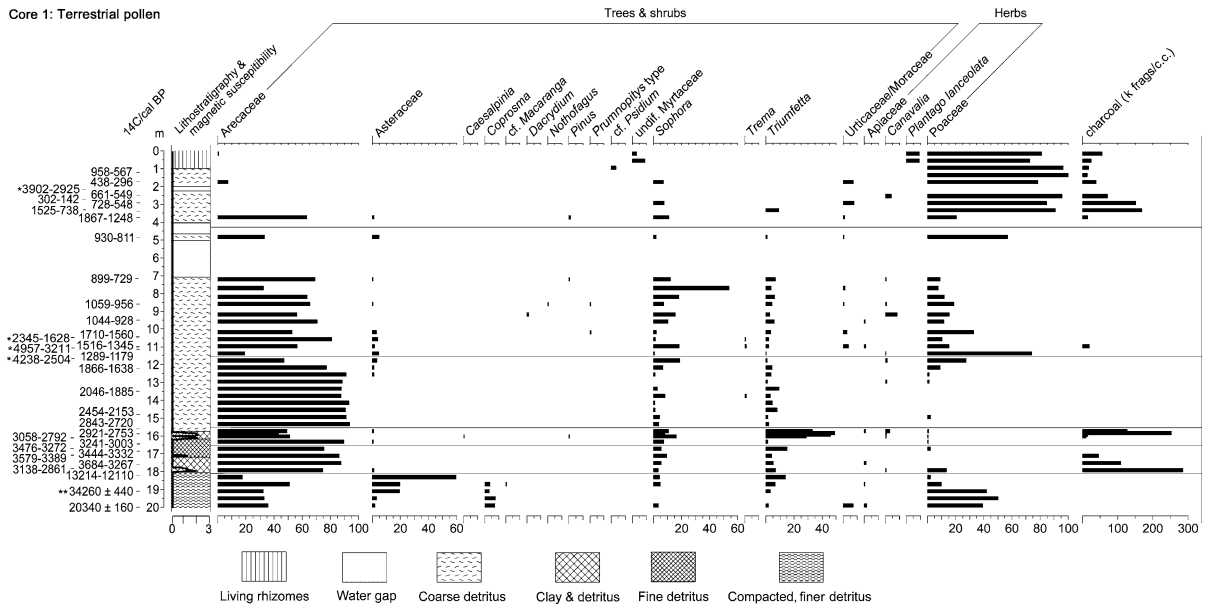


Fig. 3 Pollen percentage diagram from Rano Kau: Trees and shrubs, Herbs; * = ants, ** = bulk sediment, remaining dates are plant macrofossils; horizontal lines show approx. levels of major change

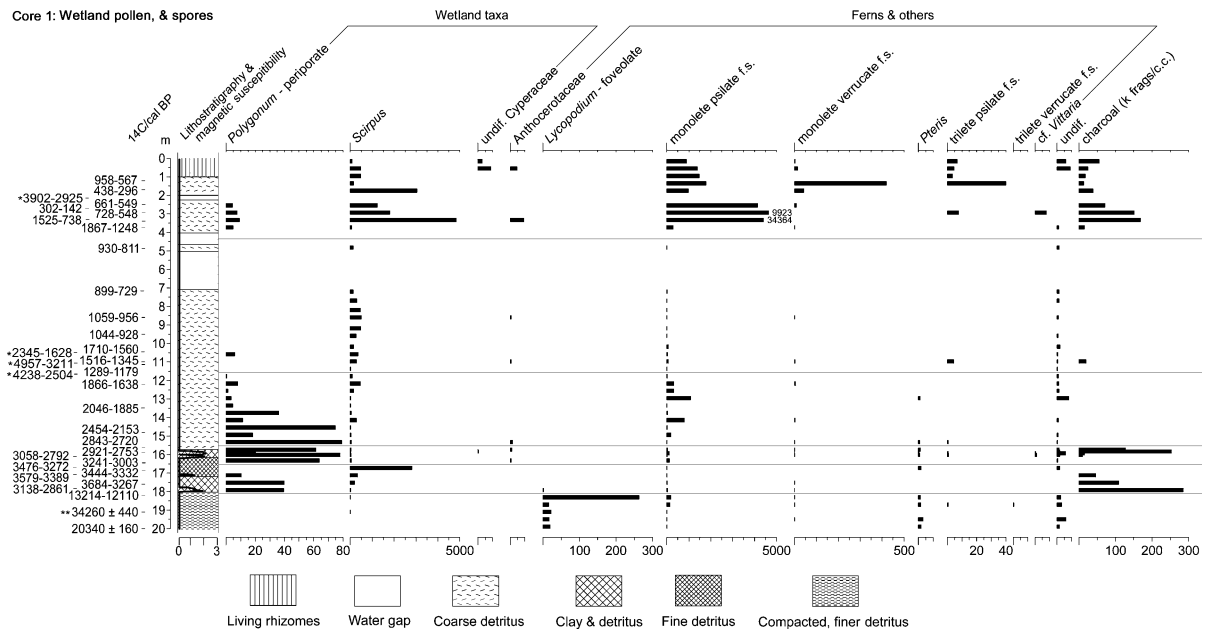


Fig. 4 Pollen percentage diagram from Rano Kau: Wetland taxa, Ferns and others; * = ants, ** = bulk sediment, remaining dates are plant macrofossils; f.s. = fern spores; horizontal lines show approx. levels of major change

Arecaceae pollen increases, at 18.0 m depth in the lower clay/detritus layer. Also in this sample charcoal first appears, in a very high concentration. *Sophora*, *Triumfetta* and especially Arecaceae dominate the

pollen sum from 17.2 cm depth through the overlying layers of up to the coarse detritus at 15.75 m depth. Charcoal was not present in the samples from the fine detritus layer, at 16.8 and 16.4 m depths, resuming in

the subsequent samples, including one with another very high concentration. *Scirpus* and *Polygonum* pollen appears in very large amounts around these depths. *Triumfetta* pollen peaks sharply around 16 m depth and *Polygonum* pollen declines shortly thereafter, followed by a peak in monolete fern spores. Charcoal disappears after ~16 m depth. Small amounts of Anthocerotaceae spores were found in the upper clay layer (and in a few subsequent samples from the overlying coarse detritus).

Areaceae, *Sophora* and *Triumfetta* pollen continue to feature in the coarse detritus, with an increase in Poaceae pollen after 12.5 m depth (Figs. 3, 4). Charcoal appears again in a small amount in one sample, at 11 m depth. Areaceae pollen declines dramatically after 3.7 m depth, replaced largely by Poaceae and *Scirpus* pollen and fern spores, the latter initially in very large amounts. There is a sustained

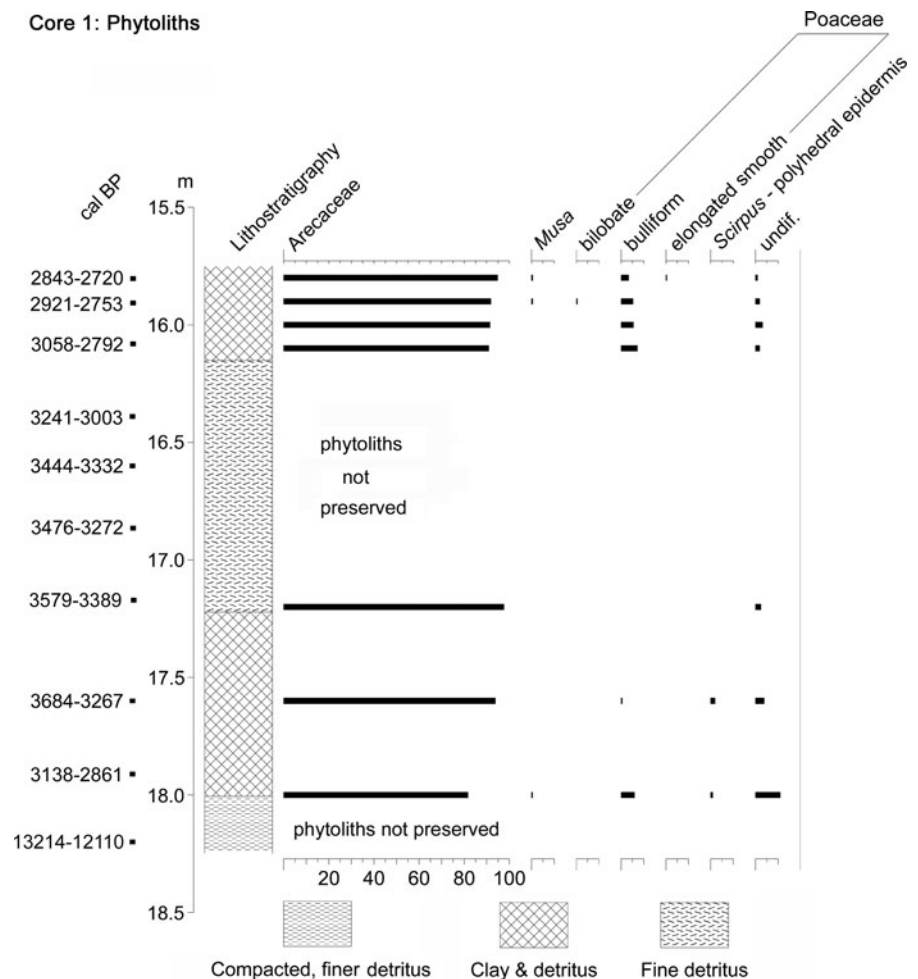
reappearance of charcoal at this time, with particularly large initial amounts.

Small amounts of several exotic pollen types were found in the core from 16.1 to 3.7 m depth, namely *Nothofagus*, *Pinus* and Podocarpaceae (*Dacrydium* and *Prumnopitys* types) (Figs. 3, 4). Some other exotic types, notably cf. *Psidium*, undif. Myrtaceae and *Plantago lanceolata*, first appear at 0.9 m depth.

Phytoliths

Phytoliths were preserved only in the clay/detritus layers of the core, with Areaceae phytoliths dominating, and small amounts of Poaceae phytoliths present (Fig. 5). Also, small amounts of *Musa* (banana) phytoliths were found in both clay/detritus layers, at 18.0, 15.9 and 15.8 m depths (Electronic Supplementary Material 1). *Musa* phytoliths are

Fig. 5 Phytolith percentage diagram from Rano Kau



diagnostic (Mindzie et al. 2001) and therefore unequivocal. No other biosilicates, such as diatoms, were found.

Arthropods

Fossil insects and mites were found in 25 of the 34 Rano Kau samples examined (Table 2). They occur as disarticulated skeletal elements with no abrasions or, except for the uppermost ant remains, post-mortal pitting. Several weevil (Curculionoidae) fragments were found in samples from 20.0 to 7.8 m depth. The fragments are of two species of Cossoninae of the tribe Dryotribini. The identifications are (Guillermo Kuschel, pers. commun.):

Genus sp. 1: 4 heads, 6 prothoraces, 13 elytra, 2 first two-fused ventrites. Estimated size of species: 2.5–2.9 mm.

Genus sp. 2: 7 heads, 2 prothoraces, 15 elytra, 1 meso/metasternum, 1 abdomen base (=first two ventrites). Estimated size of species: 3.4–3.6 mm.

Allodessus skottsbergi (Zimmerman) (Dytiscidae) fossils were found in most of the samples above 15.5 m (Table 2). Dytiscids are predacious diving beetles. *A. skottsbergi* is described in Balke and Ribera (2004) and the type location for this species is Rano Kau. It is found in the crater lake of Rano Kau under algae (Zimmermann 1924).

Two species of ant (Formicidae) were identified in the core (Table 2, Electronic Supplementary Material 2). The first, of which a single head was found, is identified as *Pheidole*, either *P. rugosula* Forel or a *Pheidole* species very close to this (Darren Ward, pers. commun.). This was found in the sample from 11.0 m depth. The second species is identified as *Tetramorium bicarinatum* (Nylander), remains of which were recovered from samples at 11.0–11.05, 10.95–11.0, 2.6 and 0.2 m depths. Only the latter has been found in Rapa Nui ant surveys (Wheeler 1922; Wilson 1973; Morrison 1997).

A species of non-biting midge (*Chironomus*: Chironomidae), a species of shore fly (Ephydriidae) and an oribatid mite (Oribatida) complete the arthropod assemblage (Table 2). A single specimen of *Chironomus* was found in the sample from 10.95 to 11.0 m depth. The fossils of the shore fly are larval stage and numerous in samples above 11.5 m. Only one specimen was recovered from deeper samples. Shore fly larvae occupy a diverse range of habitats

Table 2 Fossil arthropod taxa from Rano Kau core 1

| Depth (m) | 0.2 | 0.8 | 1.4 | 2.6 | 3–0 | 4.7 | 7.2 | 7.8 | 8.5 | 9.2 | 9.6 | 10.3 | 10.95–11.00 | 11.0 | 11–11.05 | 11.5 | 12.2 | 13.3 | 15.1 | 15.5 | 16.5 | 17.0 | 17.5 | 19.5 | 20 | |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|-------------|------|----------|------|------|------|------|------|------|------|------|------|----|---|
| Dytiscidae: <i>Allodessus skottsbergi</i> | 1 | 1 | | 2 | 2 | 1 | 2 | 1 | 1 | | 1 | 5 | | 7 | 2 | 2 | | 1 | 1 | 1 | | | | | | |
| Curculionoidae: Cossoninae genus sp. 1 | | | | | | 2 | | 1 | 1 | 1 | | | | | | | | | | | 1 | | | 1 | | |
| Curculionoidae: Cossoninae genus sp. 2 | | | | | | 1 | 2 | | 1 | | | | 3 | 1 | | 1 | 1 | 1 | | | 1 | 1 | 1 | 1 | 1 | 1 |
| Formicidae: <i>Tetramorium bicarinatum</i> | | | | 1 | | | | | | | | 1 | | 2 | | | | | | | | | | | | |
| Formicidae: <i>Pheidole</i> sp.1 cf. <i>P. rugosula</i> | | | | | | | | | | | | | | 1 | | | | | | | | | | | | |
| Ephydriidae sp.1 | | | 1 | | | | 3 | 2 | 2 | 2 | 1 | 7 | 2 | 9 | 2 | 2 | | | | | | | | | 1 | |
| Chironomidae: <i>Chironomus</i> sp.1 | | | | | | | | | | | | 1 | | | | | | | | | | | | | | |
| Oribatida sp.1 | | | | | | | | | | | 1 | | 2 | 2 | | | | | | | | | | | | |

including freshwater bodies, and the larvae of many species are phytophagous, with some grazing on aquatic plants and others on algae. The oribatid mite was found in three samples, from 11.05 to 10.3 m depth.

Discussion

The pre-Holocene environment and an early to mid-Holocene hiatus

The two lowermost, inverted, ^{14}C dates from the Rano Kau core, $20,340 \pm 160$ BP and $34,260 \pm 440$ BP at 20 and 19.1 m depths respectively in the basal, compacted fine detritus, indicate that the record commences several millennia prior to or during the LGM (Figs. 3, 4). The oldest date at 19.1 m depth is a bulk sediment date, with contaminants perhaps explaining its older age (Bennike 2000). The dates, combined with the stratigraphy at these depths, suggest records may be obtainable extending through the LGM, if suitable coring equipment is used. The pollen evidence, in particular the high values of Poaceae pollen and much lower than subsequent Arecaceae values, suggests that the local vegetation at the time was mostly grassland-woodland or small forest patches, with woodland comprising Arecaceae and smaller amounts of Asteraceae, *Coprosma*, *Sophora* and *Triumfetta*. This limited forest environment is consistent with pollen studies from elsewhere on the island suggesting cooler/drier conditions during this time (Flenley et al. 1991; Azizi and Flenley 2008). Arecaceae is generally considered a warm climate indicator, rarely extending outside the tropics and sub-tropics (Good 1953), and also recorded lower pollen levels at Rano Raraku during the LGM (Flenley et al. 1991).

Further evidence of cooler LGM conditions in our core could be the presence of foveolate *Lycopodium* spores, and their absence in the Holocene, throughout the compacted deposit (Figs. 3, 4). The only Rapa Nui pollen site where this taxon has been recorded throughout deposits of the warmer Holocene is Rano Aroi, at 425 m the highest altitude and coolest climate pollen site on Rapa Nui (Flenley et al. 1991). The only climatic analogy we can find is the South American Andes, where *Lycopodium* is thought to be an indicator of cool conditions (Van't Veer and Hooghiemstra 2000; Van't

Veer et al. 2000). Notwithstanding likely sediment compression, the long time span of at least *c.* 10,500 years relative to the short distance between the two lower samples and upper dated sample (13,214–12,110 cal BP) from the compacted layer suggests a low deposition rate, providing evidence for dryness. The paucity of wetland pollen in this deposit supports this. Coincident lack of charcoal, however, suggests a low frequency of natural fires.

The two weevil (Curculionidae) species identified in the Rano Kau core, first appearing in the pre-Holocene deposits, have not previously been described for Rapa Nui. Only two weevil species of the Pacific Island realm are currently known to occur on Rapa Nui. One is an anthribid species, *Dinema filicorne* Fairmaire, described from Fiji, the other a curculionid species, *Pacindonus bryani* (Swezey), described from Rapa Nui and presumed endemic as it has not been reported elsewhere (Guillermo Kuschel, pers. commun.). Cañellas-Boltà et al. (2012) identified a fossil weevil species in their sediment core from Rano Raraku, describing it as a member of either Molytinae or Cossoninae. Our two weevil species are identified as belonging to Cossoninae: Dryotribini, but they differ in morphology than the examples illustrated in Cañellas-Boltà et al. (2012). Our two weevil species are thus new indigenous species for Rapa Nui.

In the upper part of the basal, compacted fine detritus, during the Late Glacial, the increase in Asteraceae pollen at the expense of Poaceae pollen suggests an increase in shrubland at the expense of grassland (Figs. 3, 4). Asteraceae recorded high pollen values during the late Pleistocene at higher altitude and cooler Rano Aroi (Flenley et al. 1991). On other Pacific Islands, for example Juan Fernandez, Rarotonga, Hawaii and Rapa, shrubby Asteraceae occur especially just above the altitudinal forest limit or in the uppermost forest (Brown 1935; van Steenis and van Balgooy 1966). Thus, although the climate at Rano Kau may have remained sufficiently cool to preclude increased forest cover, the decrease in grassland and increase in shrubland suggests alleviating conditions nearing the start of the Holocene, at 13,210–12,110 cal BP.

The period encompassing the very late Glacial to the late Holocene, *c.* 12,500–3,500 cal BP, appears to be missing from our Rano Kau record (Figs. 3, 6). Based on ^{14}C evidence, Gossen (2007) suggested a

major decrease in the Rano Kau sedimentation rate during 8,370–3,470 BP due to dryness. Rano Raraku core studies suggested a lower lake level from *c.* 9,500 cal BP with swamp and shallow lake conditions dominating until the mid-Holocene, then drying after 4,100–4,500 cal BP (Mann et al. 2008; Sáez et al. 2009; Cañellas-Boltà et al. 2012; Horrocks et al. 2012b). In addition, given the disturbed nature of the deposits immediately overlying those of the pre-Holocene, the Rano Kau deposits representing the early to late Holocene, assuming deposition occurred, could have in part been lost as a result of human activity during droughts. This could include burning of peaty material, or desiccation and removal of peaty material by wind erosion following exposure.

The Late Holocene environment and human activity

The Rano Kau record continues immediately above the compacted detritus layer, in the lower of the two clay/detritus layers, which appears to be associated with human activity. This is evidenced by the very high concentration of charcoal fragments and presence of introduced *Musa* (banana) phytoliths in the sample from 18.0 m depth, near the base of this layer (Figs. 3, 4 and 5). This lowermost clayey layer, with dates collectively between 3,680 and 2,860 cal BP, could be considered to represent an erosion event as a result of early forest clearance by fire and associated agriculture, but would require an explanation for dates much older than expected for Polynesian arrival (Kirch et al. 2010; Wilmschurst et al. 2011).

The *Scirpus* and *Polygonum* pollen peaks in the lower clay/detritus layer show that the core site is now within a wetland, with the latter, littoral taxon indicating that the immediate core site is on or near the edge of this (Figs. 3, 6). The water level and edge of the wetland thus appear to have been near this point—18 m below, and 53 m out from, the present level and edge. The pollen and phytolith evidence indicates that dryland vegetation around the wetland at the time of early Polynesian activity comprised primarily *Arecaceae*, *Sophora* and *Triumfetta*, consistent with previous Rano Kau pollen records (Flenley et al. 1991; Butler and Flenley 2001; Horrocks et al. 2012a). *Arecaceae* and *Poaceae* are over-represented in the Rapa Nui phytolith record, with many other taxa, including woody plants and

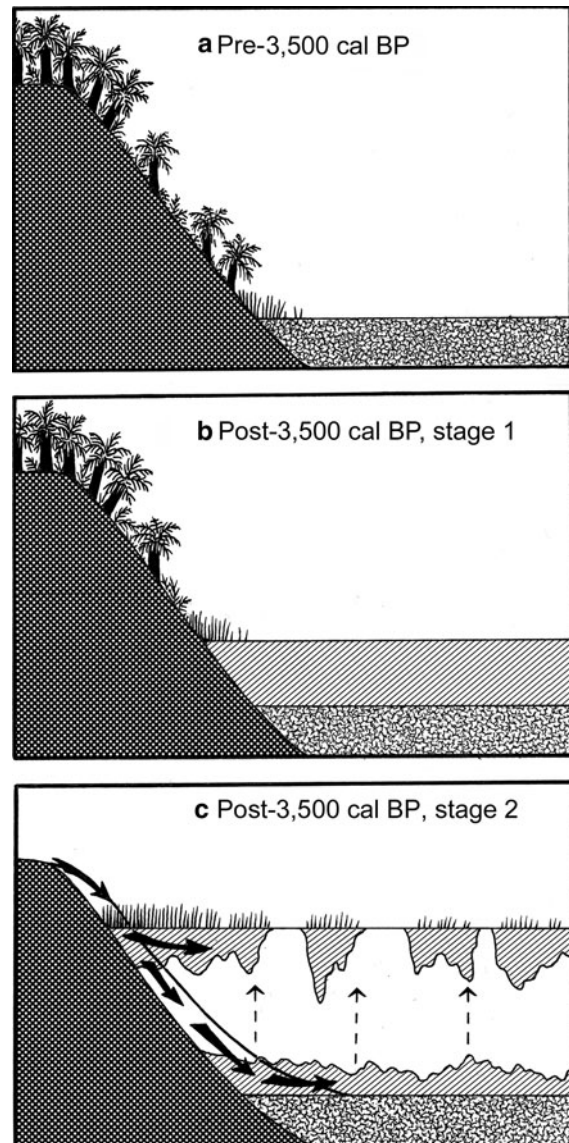


Fig. 6 Schematic diagram of Rano Kau basin, showing hypothesized late Quaternary in-filling; *water gap exaggerated*. **a** Compacted organic detritus with *c.* 12,000 cal BP surface. **b** Unconsolidated organic detritus accumulates after *c.* 3,500 cal BP, directly on top of *c.* 12,000 cal BP surface. **c** Water level rise pulls vegetation away causing floating mats, at least 958–567 cal BP, possibly a result of erosion due to Polynesian forest clearance and slumping of garden terraces on steep unstable slope. Slumping also causes variably-aged terrestrial material to settle in unconsolidated organic detritus column

ferns, poorly represented. The phytoliths thus provide evidence of the *Arecaceae* forest component only; *Sophora* and *Triumfetta* appear not to be represented in Rapa Nui phytolith spectra (Fig. 5).

The layer of fine detritus above the lower clay/detritus layer has dates collectively between 3,580 and 3,000 cal BP, suggesting that it is of similar age to the former. However, the apparent absence of charcoal in this layer suggests that, unlike the clay/detritus layer, it is not associated with human activity (Figs. 3, 4). Fine detritus indicates open water, with algae as opposed to larger plants contributing greatly to the sediment. Explanations for this late Holocene inundation commencing at an undetermined time after 3,500 cal BP include an increase in rainfall (although there is no independent evidence for this), early to mid-Holocene sea level rise reducing seepage, and natural and human-induced landslides and erosion blocking seepage channels. Flooding as a result of reduced water storage and run-off buffering of slope forest vegetation and soils following forest clearance by people could also be expected.

The subsequent deposit, the second clay/detritus layer with dates collectively between 3,060 and 2,750 cal BP and also containing *Musa* phytoliths and abundant charcoal, suggests a further episode of cultivation and another erosion event soon following the first (Figs. 3, 4). The Anthocerotaceae spores in this layer provide further evidence for this. These have been found in the previous study from this sector of the lake, and elsewhere in Rapa Nui and wider Polynesia, in association with human landscape disturbance and agriculture (Wilmschurst et al. 1999; Horrocks et al. 2012a, b).

The clay/detritus layers with charcoal and cultigen remains in the Rano Kau core represent clayey soils eroded as a result of disturbance of the crater slopes by people. The dates in these layers, however, collectively ranging from 3,680 to 2,750 cal BP, are well before the generally accepted timing of settlement of Eastern Polynesia (Kirch et al. 2010; Wilmschurst et al. 2011). The age-depth model (Fig. 2) suggests that a period of continuous deposition during this period is plausible, but the possibility of incursion into the sediment column from an erosion event should be considered (Fig. 6). This would not be unexpected given the proximity to a steep occupation site and was suggested for the similarly older than expected dates found in the four late Holocene cores from this sector of the lake (Horrocks et al. 2012a). This explains the combined evidence, but is challenged by the consistent accumulation obtained through additional ^{14}C dating to test this hypothesis.

The small amounts of *Musa* phytoliths found at this stage preclude direct dating.

Other potential causes of earlier than expected ^{14}C dates could be due to ‘the hard water effect’ (Olsson 1986), if some of the unidentified fruits/seeds dated derived their carbon from the water rather than the air. For this to occur, aqueous CO_2 would need to be from peat decomposition, presumably during a phase of drying. Carbonate-rich rock can be ruled out as a source of hard water in the volcanic environment of Rapa Nui, but volcanic CO_2 sourced through the water and/or emitted to the atmosphere could cause localised increases in apparent ages, by mixing ^{14}C -dead CO_2 with aquatic or atmospheric CO_2 . Given the large, possibly drought-induced hiatus, with late Holocene deposits lying directly on top of much older, pre-Holocene deposits, the potential for this could be high. However, there is evidence for volcanic activity on Rapa Nui during the period in question, despite dormancy during the historic period (Gonzalez-Ferran et al. 2004).

In support of the Bayesian age-depth model in Fig. 2, it appears the model is consistent with Polynesian arrival at ~11.1 m depth, if a reservoir effect of 750 ± 200 years can be assumed. This would imply that the floating vegetation mat had emerged at this time, and is consistent with both the average ages of dates obtained in the floating mat and the age estimated for the top of the sediment column by the age-depth model. This calculation would then imply an approximate age for the 11.1 m section of the core of 750 ± 200 BP, consistent with the Kirch et al. (2010) and Wilmschurst et al. (2011) respective estimates of c. AD 1,000 and AD 1,190–1,290 for Polynesian settlement. The decline in Arecaceae and sharp peak in Poaceae pollen around this depth, along with evidence of charcoal, make a plausible case for this depth as worthy of consideration as the time of Polynesian arrival (Figs. 3, 4).

Evidence for human arrival at or below 16 m depth in the core must also be considered. During this period of apparent major forest disturbance at Rano Kau, the upper clay layer shows a high *Triumfetta* pollen peak at the expense of Arecaceae pollen (Figs. 3, 4). This could reflect a successional *Triumfetta* response following natural or human forest disturbance, including selective logging of Arecaceae for straight logs or cultivation of *Triumfetta* from which rope was manufactured (Horrocks et al. 2012a). Alternatively, if the

disturbance at ~16 m depth was natural, and human arrival occurred from 11 m depth, the continuing presence of *Triumfetta* pollen above this interval would be consistent with the above explanations, and the timing of Arecaceae decline.

The coarse lake detritus overlying the upper clay/detritus layer in the Rano Kau core indicates a reduction of open water in the vicinity of the core hole, with increased input of aerial wetland plant material, namely *Scirpus*, *Polygonum* and ferns (Figs. 3, 4). We interpret this layer as representing a much less disturbed deposit, with initial deposition occurring c. 2,800–2,700 cal BP, which as with the preceding fine detritus layer, was well before people are thought to have arrived. The decrease in *Polygonum* pollen over the subsequent c. 1,000 years suggests a continuing rise in lake level, with the core site becoming progressively more distant from the shore. The first appearance of diving beetles (Disticidae) at 15.5 m depth, near the lower boundary of this deposit, supports this contention as these are mainly found in stagnant/still water (Ordish 1966). The origin of our dysticid species, *Allodessus skottsbergi*, is uncertain, although it is likely to be indigenous to Rapa Nui (Ignacio Ribera, pers. commun.).

As noted above, evidence of landscape disturbance in the coarse detritus layer is apparent approaching 11 m depth, with the increase in Poaceae pollen and limited evidence of charcoal (Figs. 3, 4). In addition, although midges (Chironomidae), shore flies (Ephydriidae) and mites (Oribatida) are found in a variety of environments and may not necessarily indicate particular conditions, their coincident appearance or proliferation in our core at ~11 m depth could be linked to this disturbance (Table 2). Remains of two ant (Formicidae) species, namely *Pheidole* sp. and *Tetramorium bicarinatum*, also found around this depth, suggest human activity again as the cause of this apparent disturbance. Eastern Polynesia has numerous ant species, all thought to be introduced as a result of ‘human’ or ‘foreign commerce’, although the literature appears unspecific about any Polynesian role in this (Wheeler 1922; Wilson 1973; Morrison 1997). The minimum age determinations for three of our four ant samples, however, are \geq c. 2,500 cal BP. Like the plant microfossil dates associated with the *Musa* phytoliths, these are much older than the generally accepted time of human settlement of Eastern Polynesia.

We consider possible explanations for the older than expected Rapa Nui ant dates:

1. People visited Rapa Nui and therefore presumably other, less remote islands in Eastern Polynesia millennia before the currently accepted time of settlement, inadvertently introducing ants. However, to our knowledge none of the numerous archaeological excavations and other examinations encompassing virtually all Eastern Polynesian islands, including Rapa Nui, show evidence to support this. Also, plant microfossil (mostly pollen) sediment cores from elsewhere in Eastern Polynesia, including other Rapa Nui wetlands, show no convincing proxy evidence supporting this.
2. The ants are indigenous to Rapa Nui. Based on more thorough surveys, Morrison (1997) found that remote Polynesian islands generally were not as depauperate in terms of ant species as previously thought. Late Quaternary fossil arthropods in Remote Oceania are under-researched, to our knowledge limited to only one previously published study, also from Rapa Nui, and this does not report ants (Cañellas-Boltà et al. 2012). Fisher (2009) discussed oceanic ant dispersal, noting floating vegetation as a mechanism and also that newly inseminated queens taking wing to establish new colonies can be blown across the open ocean. Phoresy is a dispersal mechanism also worth considering, especially given that the prehistoric seabird fauna of Rapa Nui probably exceeded 30 species, more than are known from any other single Polynesian island (Steadman 1995). In addition, passive internal dispersal of insects, dead or alive, via animals, especially birds in our case, cannot be ruled out (Green and Sánchez 2006; Hernández 2011).
3. The ants had been ingesting old carbon within food webs in the catchment. This is suggested by their apparent ages older than those of the plant macrofossils from around the same depths. Beavan-Athfield et al. (2001) dated modern rats from New Zealand up to >2000 years old. That case involved the transfer of ^{14}C depleted carbon to lake waters by geothermal venting, which aquatic plants fix into the food chain.

Regardless of the timing uncertainty, we interpret the aforementioned disturbance indicators at ~11 m depth as the result of further regolith upheaval and erosion events. The disordered dates of plant macrofossils from 11.1 to

10.4 m depth support the contention of either in-washed material and/or variability associated with pre-aged material sloughing from the floating vegetation mat (Fig. 6). Other pollen indicators of forest disturbance around the same time are Anthocerotaceae, *Trema* and Urticaceae/Moraceae, first occurring during this period in the same sample as the small amount of charcoal at 12 m depth. *Trema* and Urticaceae/Moraceae taxa are two of the several indigenous plant taxa now extinct as a result of human activity. Identification of Polynesian-introduced *Broussonetia papyrifera*, of the Moraceae, in the Rapa Nui pollen record is therefore complicated.

The floating vegetation mat provides for some clear interpretations, but contains material of mixed ages with a trend of increasing age with depth despite apparent inversions (Fig. 2). True inversions are not unexpected in the floating mat, given that it is not continuous across the lake surface (Fig. 1). Infiltration of older carbon into the sediment column causing some of the inverted dates in this and previous Rano Kau studies could also involve mechanical disturbance of the column. Given the considerable steepness and height of the crater walls, small tsunamis generated by landslides could be expected to cause major disturbance, including inversion of floating lake deposits.

Evidence of major landscape disturbance by people is widely present in the floating mat, from 4 m depth to the top of the core. The large amounts of charcoal and permanent disappearance of Arecaceae, Asteraceae and *Triumfetta* pollen indicate large-scale clearance of remaining forest by fire (Figs. 3, 4). Several inverted dates, including one of more ant remains within this section of the deposit, reflect erosion of pre-aged material into the lake as a result (Table 2, Fig. 6).

The pollen of cf. *Psidium*, undifferentiated Myrtaceae and *Plantago lanceolata* in the uppermost, 1 m-deep layer of living rhizomes in the Rano Kau core reflects European influences (Figs. 3, 4). The other exotics found in the core, namely *Pinus*, *Nothofagus*, and *Dacrydium* and *Prumnopitys* types, all with long-distance pollen dispersal, are most likely wind-transported from other parts of the world.

Conclusions

The results from Rano Kau extend the local vegetation-climate record to at least the LGM, providing the oldest ^{14}C dates thus far for this wetland and

suggesting that much older cores could potentially be obtained. The pre-Holocene vegetation, interpreted as reduced forest cover reflecting cooler/drier conditions, with open areas in forest changing from a largely Poaceae component to increased shrubland approaching the Holocene c. 12,500 cal BP, is consistent with records from the other Rapa Nui wetlands. As we were prevented from coring deeper by compaction rather than basal rock, the Rano Kau record could be extended further.

The inclusion of introduced *Musa* (banana) phytoliths in in-washed clayey material in late Holocene deposits in the core appears to allow unequivocal association with human presence. However, the dates for plant macrofossils associated with the phytoliths, within the consistent sediment accumulation in the age range 3,680–2,750 cal BP, would require an explanation such as a consistent source of ^{14}C -dead CO_2 to be accepted as agreeing with the accepted timing of Polynesian arrival. More broadly, the core contains a progressively younger upward sequence from 18 to 7 m depth and plausible explanations for variable episodes, particularly at c. 11 m depth as being due to deposition of pre-aged material from the floating vegetation mat or erosion events. The hypotheses to explain the observed dates appear to warrant further exploration using field investigations or more formal Bayesian modelling techniques building on Fig. 2.

The arthropods found in the Rano Kau core, almost entirely insects, include two new weevil species for Rapa Nui, and two ant taxa, *Tetramorium bicarinatum* and *Pheidole* sp., the latter of which is also new for the island. As Eastern Polynesia's ant species are all thought to have been introduced, the ^{14}C ages on the ant exoskeletons all date to well before the generally accepted timing of settlement, suggesting that natural ant distributions were far wider than previously thought. or that apparent ^{14}C ages have been increased by reservoir effects. If the Rapa Nui ants are indigenous, this has implications for ant introductions versus indigenes elsewhere in Polynesia, and therefore for using fossil ants as an indicator of human presence.

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