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Drought, vegetation change, and human history on Rapa Nui (Isla de Pascua, Easter Island)

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Abstract

Stratigraphic records from lake sediment cores and slope deposits on Rapa Nui document prehistoric human impacts and natural environmental changes. A hiatus in sedimentation in Rano Raraku suggests that this lake basin dried out sometime after 4090–4410 cal yr BP and refilled only decades to centuries before AD 1180–1290. Widespread ecosystem changes caused by forest clearance by Polynesian farmers began shortly after the end of this drought. Terrestrial sections show a chronology of burning and soil erosion similar to the lake cores. Although changing sediment types and shifts in the pollen rain suggest that droughts occurred earlier in the Holocene, as yet there is no evidence for droughts occurring after AD 1180–1290. The timing of the agricultural colonization of Rapa Nui now seems well established at ca. AD 1200 and it was accompanied by rapid deforestation that was probably exacerbated by the island's small size, its droughty climate, and the rarity of primeval fires. Detailed records of a large interval of Rapa Nui's ecological history remain elusive due to the drought hiatus in the Rano Raraku sediment record. We find no evidence for a "rat outbreak impact" on Rapa Nui's vegetation preceding anthropogenic forest clearance.

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Keywords: Easter Island; Rapa Nui; Island ecology; Polynesian archaeology; Pollen analysis; Fire history; Drought; Island microcosm; Rat impacts

Introduction

The small and isolated island of Rapa Nui may be a microcosm for the planet Earth (Kirch, 1997), and its history could hold important lessons for our collective future (Bahn and Flenley, 1992; Diamond, 2005, 2007). Unfortunately, the environmental history of this island is poorly understood. What we do know is that prior to the arrival of Polynesian farmers, much of Rapa Nui was covered with forests dominated by a now-extinct species of palm (Flenley et al., 1991; Orliac, 2000). Also, the island was home to at least five species of endemic, flightless birds and supported colonies of sea birds that no longer occur

there (Steadman et al., 1994; Steadman, 2006). Although it remains unclear when humans first discovered Rapa Nui (Hunt and Lipo, 2006; Flenley and Bahn, 2007), the onset of agricultural settlement is clearly marked by the destruction of the primeval forest and soil cover starting ca. AD 1200 (Hunt, 2007). We also know that between AD 1200 and 1650, an agrarian society erected huge sculptures and transformed both the terrestrial and nearshore ecosystems of Rapa Nui. The human population rose to an unknown level, possibly more than 10,000 people (Diamond, 2005). Around AD 1650, a societal collapse occurred that was accompanied by warfare, a crash in population size, and striking cultural changes (Bahn, 1993; Diamond, 2005). When James Cook visited Rapa Nui in AD 1774, he found perhaps a thousand people eking out a living amidst megalithic ruins on an island barren of trees (Heyerdahl, 1961).

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Our existing knowledge of the prehistory of Rapa Nui has been interpreted in quite different ways. One interpretation, which originated with the French explorer Comte de La Pérouse in AD 1786 (La Pérouse, 1968) and has been further developed by others (Mulloy, 1970; Flenley and King, 1984; Flenley et al., 1991; Bahn and Flenley, 1992; Diamond, 2005, 2007), is that the uncontrolled growth of the human population destroyed the natural vegetation, degraded the island's ecosystems, and eventually led to the near extinction of the human inhabitants. By felling all the trees, partly to help move large stone sculptures around the island, the people destroyed their ability to make boats and to escape from the ecosystems they had degraded. This interpretation of Rapa Nui's history has been used as the basis for developing general models for human use of natural resources (Brander and Taylor, 1998; Dalton and Coats, 2000; Reuveny and Decker, 2000) and is even portrayed in a Hollywood movie (Reynolds, 1994). Diamond (2005) makes Rapa Nui a centerpiece in his review of how human societies can self-destruct by overexploiting their natural resources.

Hunt (2006, 2007) proposes a different interpretation of human history on Rapa Nui, pointing out the lack of evidence that societal collapse actually coincided with the Polynesian transformation of the island's ecosystems. He suggests that deforestation and biological impoverishment occurred rapidly after human arrival but then stabilized in a transformed but still viable state over the next four to five centuries. Hunt (2007) believes that during this time, the human population maintained itself at a size much smaller than previously speculated, and he hypothesizes that the eventual collapse of this society was triggered not by self-induced, ecological overexploitation but by contact with European explorers. One trigger could have been the familiar scenario of European disease organisms being introduced into an immunologically naive population by contact with European sailors. Hunt (2006, 2007) goes on to speculate that the initial deforestation of Rapa Nui was a collaborative impact of Polynesian settlers and their commensal rat, *Rattus exulans*. Drawing on studies of rat impacts on islands (Athens et al., 2002; Towns et al., 2006), he suggests that rapidly reproducing rats may have done more damage to the native plants and animals during an irruptive, rat-outbreak interval than the Polynesians did later.

Yet another interpretation of events on Rapa Nui holds that environmental changes beyond the control of humans triggered the societal collapse (McCall, 1993; Nunn, 2000; Orliac and Orliac, 2005). Diamond (2005) notes that, on a global basis, external environmental changes have been involved in many cases of societal collapse. Flenley and Bahn (2007) agree that environmental changes probably conditioned the social history of Rapa Nui. Unfortunately, the paleoenvironmental history of Rapa Nui is too poorly known to test hypotheses involving climate change as causes of societal collapse. Compounding the problem, the island is so geographically isolated that it is difficult to infer its environmental history from better known regions.

Here we report on sediment, charcoal, and pollen stratigraphy in lake cores from Rapa Nui and integrate these results with the preliminary report of Mann et al. (2003) on the ages of charcoal fragments found in colluvial deposits on the island. These results help identify the timing of widespread forest

clearance and help test hypotheses about the occurrence of a rat-outbreak impact and the involvement of droughts in human history on Rapa Nui.

Study area

Comparisons with other Pacific islands suggest to Rolett and Diamond (2004) that Rapa Nui (Fig. 1) was predisposed to species extirpations after human settlement because of its relatively low relief, low rainfall, and its geographic isolation. Rapa Nui is volcanic in origin and has a surface area of only 164 km², which makes it possible to walk across the island in several hours. Although large coral heads occur around the island (Mucciarone and Dunbar, 2003), cool ocean waters prevent the formation of a fringing coral reef. The island's topography consists of the rounded slopes of volcanic cones and the rolling surfaces of the lava flows between them. Several species of introduced birds, together with horses, cattle, cats, dogs, and the ship rat (*Rattus rattus*) occur on the island today. Pigs and goats were introduced by European visitors in the AD 1700s, while sheep and cattle were introduced by missionaries ca. 1866. Though rare today, approximately 40,000 sheep grazed the island in 1943 (Porteous, 1981). The only refuges for plants threatened by fire or grazing are sea cliffs and the steep walls of the Rano Kau and Rano Raraku craters. Most of the shoreline consists of lava cliffs lashed by vigorous surf. There are two lakes on the island, Rano Raraku and Rano Kau, both of which are located in volcanic craters. A third crater, Rano Aroi, contains a reed swamp. The island's one permanent surface stream originates at Rano Aroi and flows for about a kilometer before disappearing underground. An indication of the surface aridity of Rapa Nui is given by the fact that plans for agricultural improvement in modern times stipulate irrigation using water pumped from the crater lakes or from deep wells (Porteous, 1981).

Climate

The mean annual temperature is 21°C, with January the warmest month at 24°C and August the coolest month at 18°C (Stretten and Zillman, 1984; International Station Meteorological Climate Summary, 1995). Mean annual precipitation over recent decades has been between 1300 and 1365 mm (Stevenson et al., 2006; Steadman, 2006) though rainfall is highly variable year to year (Genz and Hunt, 2003). The largest departures from the mean are associated with wetter than normal years, and these frequently involve 2–4 times more precipitation than the mean (Genz and Hunt, 2003). There is no evident correlation between the El Niño-Southern Oscillation (ENSO) and rainfall on Rapa Nui (MacIntyre, 2001; Genz and Hunt, 2003), although the ENSO does accompany shifts in the predominant wind direction (Anderson et al., 2006) and sea-surface temperature (Mucciarone and Dunbar, 2003).

Vegetation and soils

Except for scattered plantations of eucalyptus and a small number of recently planted coconut palms, Rapa Nui is presently

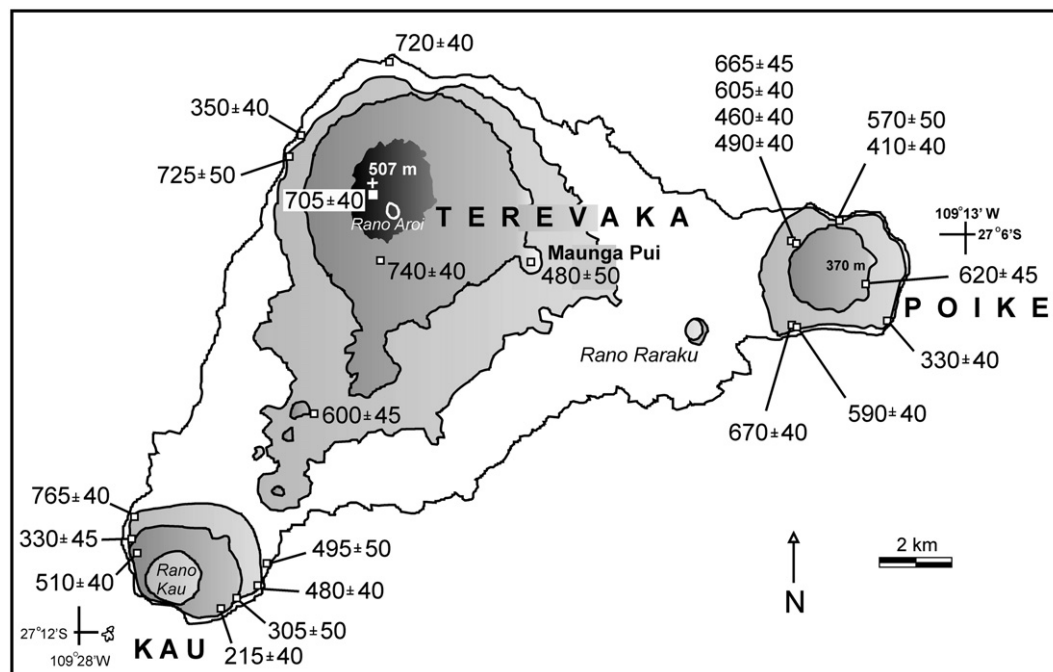


Figure 1. Rapa Nui (Isla Pascua, Easter Island) showing the three major volcanic centers of the island and the locations and ages of ^{14}C -dated charcoal collected from slope deposits.

a treeless landscape. The constant wind combined with the cool temperature and the absence of a sheltering forest discourages the growth of tropical plants including the cultigens important to early Polynesian settlers like coconuts, bananas, and breadfruit (Stevenson et al., 1999). The staple crop in prehistoric times was sweet potato (*Ipomoea batatas*) (Yen, 1974; Cummings, 1998). The present vegetation of Rapa Nui consists of about 200 species, most of which were introduced (Flenley, 1993a). Only 54 native species survive, of which eight are endemic (Skottsberg, 1956). Trees are rare and all are introduced species. Introduced grass species dominate the vegetation below about 400 m, while native sedges and bunch grasses are widespread above this altitude (Flenley, 1993a,b). Today, people use fire to maintain the lowland grasslands for grazing. Except for the eucalyptus plantations, the present-day grassy landscape of Rapa Nui is probably similar to what the earliest European visitors saw in the AD 1700s (Orliac and Orliac, 1998).

Most soils on Rapa Nui have been disturbed by removal of the primeval vegetation (Mann et al., 2003; Meith and Bork, 2005), by prehistoric agriculture (Stevenson et al., 1999, 2006), and by historic sheep grazing. The main controllers of the soil-cover mosaic are altitude, slope, the nature of the parent material (e.g., lava flow or tephra deposit), and the age of these deposits (Wright and Diaz, 1962). Small pockets of arable soils occur scattered across the rest of the island (Stevenson et al., 1999; Ladefoged et al., 2005).

Volcanoes and the Crater Lakes

Volcanoes form the three corners of Rapa Nui (Fig. 1). The oldest rocks on the island are the 0.5 Ma basalt/hawaiite flows (Hasse et al., 1997) forming the Poike stratovolcano at the

eastern corner of the island. Poike has been severely eroded by the sea on all sides. It was once an island that was later connected to Terevaka by lava flows issuing from the latter (Baker, 1967). The southwestern corner of the island is formed by another volcano, which contains the caldera lake of Rano Kau. The Kau volcano was active until ca. 0.3 Ma (Hasse et al., 1997). This volcano is intermediate between Poike and Terevaka in the degree of its sea-cliff and soil development. A third volcano, Terevaka, forms most of the landmass of Rapa Nui and supports numerous parasitic cones on its flanks. Lava flows and scoria cones arranged along volcanic fissures link Terevaka to the two older volcanoes. The broad, gently sloping dome of its summit reaches 500 m altitude. Terevaka has a complex eruptive history with most of its mass built by a series of lava flows and pyroclastic eruptions from near its present summit (Baker, 1967).

The small crater of Raraku is important for the present discussion because of the sediment cores we took from its lake, Rano Raraku. This lake is enclosed in a crater of composite origin. The crater's southeastern side is composed of tuff from which the moai statues were carved. A spectacular cliff was eroded in this tuff by the sea before lava flows from Terevaka shifted the coastline a kilometer further southeast. The Raraku tuffs dip northwestward, indicating the former vent lay to the southeast. The present crater was built around a new vent that emerged at the inland margin of this older tuff cone.

Rano Raraku is a closed-basin lake that is oval in shape and measures 320 m from east to west. The lake was lowered by about a meter after 1958 by the insertion of a pipe to serve as a water source for a neighboring farm (Flenley, 1993b). We made several transects across the lake with an echo sounder and found that it is flat-bottomed with water depths of 6–7 m in its central basin. Totoria reeds (*Scirpus californicus*) covered approximately 1/6 of

the lake surface when we were there in 1998. Some of these reeds are rooted in a fringe around the lakeshore, while the larger portion form a flotilla of mats 1–2 m thick that are redistributed around the lake by the wind. Rano Raraku has been frequently photographed, and our inspection of these photographs indicates that over the last century reed mats have never completely covered the lake, and that the locations of the floating mats are continuously changing. In this way, the vegetation mats in Rano Raraku are different from the stable mats familiar from infilling lakes at higher latitudes and from the thicker and more stable mat of totora reed that covers Rano Kau today.

Paleoecology

John Flenley carried out the pioneering work on Easter Island's ecological history by retrieving sediment cores from the island's three crater lakes and analyzing them for pollen, describing their chemical and physical stratigraphy, and obtaining radiocarbon dates (Flenley and King, 1984; Flenley et al., 1991; Flenley, 1993b). Though invaluable as a comprehensive reconnaissance, these earlier studies—like the contribution of Dumont et al. (1998)—do not provide close control on the timing of human-associated ecological events. This poor age control arises from a combination of relatively few ^{14}C -dated samples and the dating of bulk samples of lake sediment that include carbon of varying ages and origins (Butler et al., 2004; Hunt, 2007).

A close look at Flenley's pollen and sediment records from the crater lakes show that sediments dating to the purported time of Polynesian settlement ca. AD 1200—though conceivably as early as AD 400 (Kirch, 2000)—are either missing or disturbed. Sediment samples dating to 480 and 6850 ^{14}C yr BP are only 15 cm apart in his core from Rano Raraku (Flenley, 1993b). In Rano Aroi, a ^{14}C -date of 19,000 yr came from near the core top, while a modern ^{14}C age was obtained from a depth of 1 m (Flenley, 1993b). Similar age discrepancies are described in Peteet et al. (2003). The ^{14}C chronology from Rano Kau contains reversals and a lengthy age plateau, some of which may be related to the presence of a continuous, 3-m-thick floating mat of totora reeds that sheds sediment of varying ages onto the lake bed (Flenley et al., 1991; Flenley, 1996; Butler et al., 2004).

There are no continuous records of ecological change over the last 2000 yr on Rapa Nui because of the dating problems just described. Nonetheless, the existing paleoecological data do tell us several interesting things about the ecological history of Rapa Nui. First, they show that the island was largely forested in prehistoric times, in stark contrast to the present day. Species identifications based on the cellular anatomy of charcoal fragments confirms this conclusion (Orliac and Orliac, 1998, 2005; Orliac, 2000) as do descriptions of the preserved root casts of the extinct palm (Bork and Meith, 2003; Stevenson et al., 2006). Orliac (2000) speculates that a closed, mesic forest similar to that occurring today on islands in eastern Polynesia probably existed on Rapa Nui prior to Polynesian arrival. Several of the now extinct or locally extirpated tree species like the extinct *Paschalococos disperta* palm (Dransfield et al.,

1984) probably grew to large size (Meith and Bork, 2003). Their presence suggests that the primeval forest, at least locally, was more than low-statured scrub (Flenley et al., 1991; Flenley, 1993a,b).

Evidence from palynology (Flenley et al., 1991) and charcoal analysis (Orliac, 2000) indicates that an unexpectedly diverse woody flora was still present on the island between the 14th and 17th centuries AD. Another intriguing result from the first generation of pollen diagrams is that in the intact, Holocene portions of the most detailed pollen diagram (Rano Aroi), large fluctuations occurred in the percentages of palm, Compositae, grasses, and ferns prior to ca. 2000 ^{14}C yr BP (Flenley, 1993b). These vegetation changes must have been caused by climatic changes, since humans were probably not yet present on the island.

The timing of initial forest clearance on Rapa Nui by Polynesian farmers is recorded by the ages of charcoal fragments in colluvial deposits that overlie the truncated remnants of the island's primeval soils (Mann et al., 2003; Meith and Bork, 2005). In many outcrops these truncated soils can be identified by the presence of the root casts of the extinct *P. disperta* palm (Flenley, 1993b; Stevenson et al., 2006). When plotted together with the ages of palm endocarps that are either in archaeological associations, are charred, and/or are rat-gnawed, the soil charcoal ages strongly suggest that humans began widespread clearance of the forest on the Rapa Nui between AD 1200 and 1250 (Hunt, 2007).

Methods

We used a hammer-driven gravity corer to take two sediment cores located three m apart about 100 m from the southern end of Rano Raraku in 6 m of water. We worked off the edge of a floating totora mat 1.5 m thick. Because the coring device did not utilize a piston, sediment compaction shortened both cores to roughly half of their undisturbed lengths. After extruding the uppermost, fluid portions of both cores, we transported the remaining sediment cores inside their plastic core tubes after carefully sealing both ends to prevent desiccation. Cores were then stored at 4°C. In the laboratory, we split the cores and sliced them into successive 1-cm-thick samples for the measurement of loss on ignition and magnetic susceptibility (at 1-cm intervals) and for extraction of pollen and plant macrofossils. Most of the analyses are on core #1, with core #2 serving as a check on these results. We extracted plant macrofossils and charcoal by washing material through 500- and 150- μm sieves and examining the residues under a dissecting microscope. Age control on the lake cores comes mainly from AMS- ^{14}C dates on the seeds of totora. We recovered the totora seeds by washing sediments through a 250- μm sieve and then sorting the plant debris under a dissecting microscope. We identified the totora seeds from ancient sediments by comparing them to the seeds of living totora plants from Rapa Nui and coastal California. Two AMS dates from core #1 come from palm pollen grains concentrated by screening sediment through a 180- μm sieve followed by repeated 10% KOH baths, 10% HCl rinses, 5% bleach rinses, followed by final screening through 45- μm and 20- μm sieves

and inspection under the compound microscope to ascertain purity (Brown et al., 1989).

Samples (1–3 cm³) were prepared for pollen identification following standard methods of Faegri and Iversen (1989). Pollen grains were identified and counted at 400x magnification. We were assisted by a voucher collection of Rapa Nui pollen compiled by John Flenley. Pollen sums that are <300 grains come from levels where pollen is extremely scarce. Due to the abundance of sedge grains, the percentage of trees, shrubs, and herbs is based on their sum minus that of sedge. The percentage of sedge is based on the sum of trees, shrubs, and herbs and including sedge. The percentage of spores is based on the sum of trees, shrubs, herbs (minus sedge) and spores. Pollen percentage calculations were done using TILIA 2.0.b.4 and

diagrams plotted using TGVIEW 2.02 (E. Grimm, Illinois State Museum, Springfield, Illinois).

Organic content was determined using loss on ignition after an hour of heating at 550 °C (Dean, 1974). We measured magnetic susceptibility using a Bartington MS-2 susceptibility meter. Radiocarbon were calibrated using the CALIB5 program (<http://calib.qub.ac.uk/calib/>) (Reimer et al., 2004; Stuiver et al., 2007) with a southern hemisphere correction for terrestrial samples (McCormac et al., 2004). We described the sedimentology of the Rano Rarauku 1 core by examining approximately 3 cc of sediment at each 1-cm depth intervals down to the 1-meter depth in the core. Samples were physically dispersed in water within a gridded Petri dish under a dissecting microscope. We estimated the proportion of different sediment types by 25% increments.

Table 1
Radiocarbon ages of charcoal fragments in soils

Laboratory number	Field sample	Location	Latitude 27° S	Longitude 109° W	Material dated	$\delta^{13}\text{C}$ (‰)	Conventional ¹⁴ C age (yr BP)	2 σ calibrated age range (year AD)
AA25527	8-16-97 B	Gully, 180 m altitude, northeast slope Poike	6.045'	15.596'	Wood charcoal	−25.1	665±45	1290–1400
AA25528	8-16-97 B	Gully, 180 m altitude, northeast slope Poike	6.045'	15.596'	Wood charcoal	−24.9	605±40	1310–1440
AA25529	8-16-97 C	Gully, 180 m altitude, northeast slope Poike	6.045'	15.596'	Graminoid? charcoal	−15.7	460±40	1420–1620
AA25530	8-16-97 D	Gully, 180 m altitude, northeast slope Poike	6.045'	15.596'	Wood charcoal	−22.2	490±40	1400–1610
AA31151	8-16-98 A2'	Cliff-top bluff, E slope Orongo	11.628'	25.322'	Wood charcoal	−25.2	215±40	1640–1950
AA31152	8-16-98 B2	Blowout, south side Poike Peninsula	7.249'	15.656'	Palm nut fragment	−20.0	670±40	1290–1400
AA31154	8-16-98 D'	Blowout, south side Poike Peninsula	7.237'	15.548'	Palm nut fragment	−20.7	590±40	1320–1440
AA31155	8-18-98 B'	Blowout, Cabo Roggewein, Poike	7.250'	14.580'	Wood charcoal	−24.5	330±40	1480–1660
AA31156	8-18-98 C'	Gully, Cabo Roggewein, Poike	6.258'	14.426'	Wood charcoal and palm nut	−25.4	620±45	1300–1430
AA31158	8-19-98 A2'	Cliff-top bluff, western slope Orongo	10.276'	26.767'	Graminoid? charcoal	−14.5	765±40	1220–1380
AA31159	8-19-98 B1'	Cliff-top bluff, western slope Orongo	10.526'	26.857'	Unident. charred seed and stem	−11.0	330±45	1460–1790
AA31160	8-19-98 C'	Headcut, western slope Orongo	10.791'	26.697'	Wood charcoal	−23.8	510±40	1400–1480
AA31161	8-19-98 D'	Cliff-top bluff, SSE slope Orongo	11.472'	24.990'	Charred resin?	−11.8	305±50	1480–1800
AA31162	8-19-98 E'	Cliff-top bluff, SE slope Orongo	11.298'	24.641'	Graminoid? charcoal	−11.8	480±40	1410–1620
AA31163	8-19-98 F'	Cliff-top bluff, SE slope Orongo	10.925'	24.480'	Wood charcoal	−21.6	495±50	1390–1620
AA31165	8-22-98 F'	Highest closed crater on Terevaka	5.265'	22.864'	Wood charcoal	−24.2	705±40	1280–1390
AA31166	8-22-98 1A'	Crater 373.20 m, south slope of Terevaka	6.357'	22.642'	Wood charcoal	−27.6	740±40	1230–1390
AA31167	8-23-98 A'	Bluff-edge gully, Omutu, north side Terevaka	3.328'	22.448'	Wood charcoal	−26.9	720±40	1270–1390
AA31168	8-23-98 B'	Bluff edge, northwest side Terevaka	4.610'	24.076'	Wood charcoal	−25.9	350±40	1460–1650
AA31169	8-23-98 C'	Bluff edge, west side Terevaka	4.852'	24.215'	Wood charcoal	−25.4	725±50	1230–1400
AA31170	8-26-98 B'	Cliff-top bluff NE of Maunga Tea Tea, Poike	5.686'	14.919'	Wood charcoal	−25.3	410±40	1450–1630
AA31171	8-26-98 C'	Cliff-top bluff NE of Maunga Tea Tea, Poike	5.686'	14.919'	Wood charcoal	−25.5	570±50	1310–1460
AA31172	8-27-98 A'	Lower slope, east side, Maunga Tuu Tapu	8.753'	23.807'	Wood charcoal	−23.0	600±45	1310–1440
Beta-143723	8-15-98A	94-cm depth, Maunga Pui crater floor	6.480'	20.081'	Charred seeds and wood fragments	−22.8	480±50	1400–1620

Table 2
Radiocarbon ages from Rano Raraku sediment cores

Laboratory number	Depth in core (cm)	Material dated	$\delta^{13}\text{C}$ (‰)	^{13}C -adjusted radiocarbon age (year before AD 1950)	2 σ calibrated age range (cal yr BP are before AD 1950)
<i>Rano Raraku core 1</i>					
Beta-131055	13–14	Totora seeds	−26.2	830±40	AD 1180–1290
CAMS-78688	16–18	Palm pollen	−27.0	3880±40	4090–4410 BP
CAMS-78689	19.5–21	Palm pollen	−27.0	3850±40	3990–4410 BP
Beta-135105	33–35	Totora seeds	−25.0	4380±50	4730–5210 BP
Beta-143721	75–76	Totora seeds	−24.7	5200±50	5740–6000 BP
Beta-131056	96–97	Totora seeds	−25.0	5590±40	6220–6410 BP
<i>Rano Raraku core 2</i>					
Beta-135106	14–15	Totora seeds	−26.1	260±40	AD 1510–1950
Beta-135107	17–18	Totora seeds	−26.1	560±40	AD 1320–1450
Beta-135108	24–25	Totora seeds	−24.0	4320±40	4640–4970 BP
Beta-143722	50–51	Totora seeds	−24.0	5210±50	5740–6170 BP
Beta-135109	93–95	Totora seeds	−27.7	6770±50	7490–7670 BP

Charcoal abundance was determined at 1-cm intervals by the sieving method of Long et al. (1998). This involved soaking samples (1–3 cm³) in a 5% solution of Calgon, a disaggregating agent, overnight or longer to break up sediment clumps. The samples were gently washed through 125- μm and 250- μm screens and the fractions examined for charcoal under a microscope at 150–200 \times magnification. The number of charcoal grains was divided by the sample volume to determine the concentration of charcoal grains per cm³.

Results

Charcoal in colluvial deposits

As detailed in a preliminary report (Mann et al., 2003), we recovered charcoal fragments from slope deposits overlying the truncated primeval soil at localities scattered around Rapa Nui (Fig. 1). Most of the charred material we dated was wood charcoal (Table 1). Also dated were three endocarps of *Paschalococos*

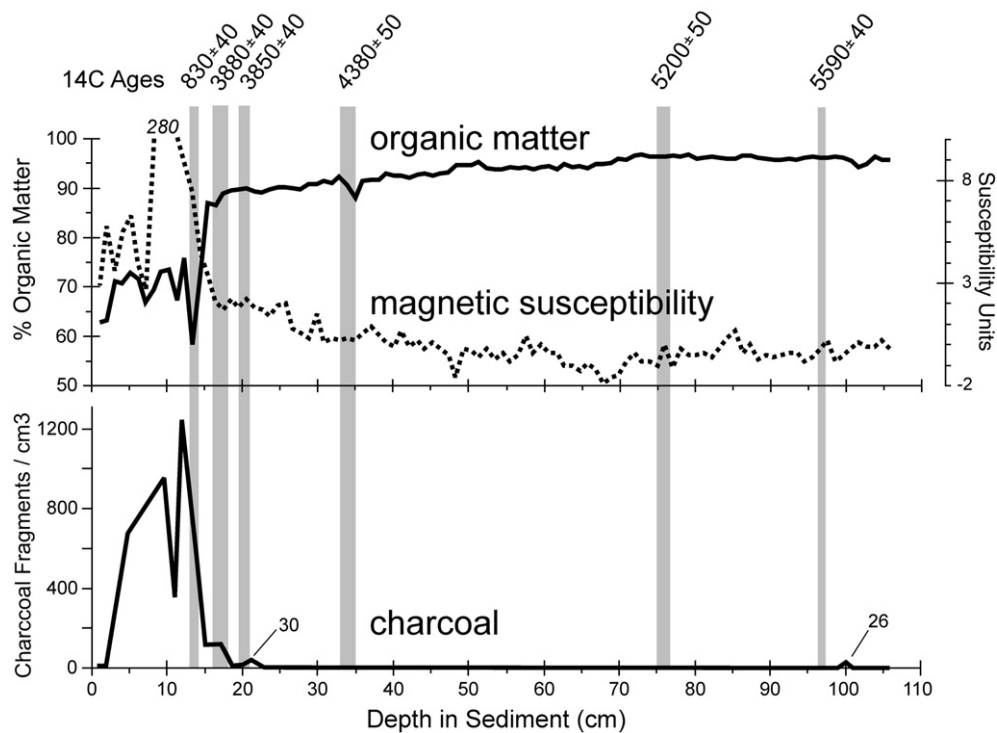


Figure 2. Stratigraphy of Rano Raraku core #1. A sharp decline in organic matter content and an increase in magnetic susceptibility indicate a major increase in the input of mineral sediment into the lake starting around the 14-cm level. The influx of charcoal fragments >125 μm increased at the same level. A major unconformity in the deposit is revealed by the close proximity of the 830 and 3880 ^{14}C yr BP dates. Charcoal fragments between the 14- and 21-cm levels could have been mixed downward into the sediment by biological activity (root channels and burrowing animals) or have been concentrated there by the decay of the enclosing sediments. Note the near absence of charcoal in sediments deeper than 20 cm. The date of 830±40 yr BP calibrates to a calendar age of AD 1180–1290 (26).

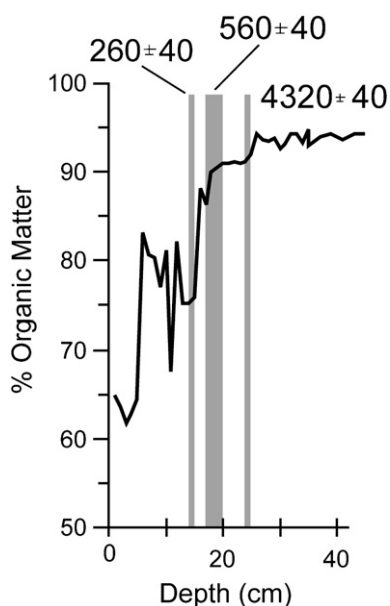


Figure 3. Organic matter content in Rano Raraku core #2 along with ^{14}C dates showing the same unconformity seen in core #1. The date of 560 ± 40 yr BP calibrates to a calendar age of AD 1320–1450 (2 δ).

disperta, four collections of finely divided charred material probably representing the burned stems of sedge or grass, an unidentified charred seed and stem, and a fragment of what appeared to be charred resin. The $\delta^{13}\text{C}$ values of the graminoid material were in the range of -11 to -16% , which are values typical of chars derived from C4 grasses (Stuiver and Polach,

1977; Krull et al., 2003). After calibration to calendar years, these soil–charcoal dates range from AD 1220 to modern (Table 1).

Sediment stratigraphy in Rano Raraku

We obtained six ^{14}C dates on core #1 ranging from 5600 to 820 ^{14}C yr BP and five dates from core #2 (Table 2). Four of the dates from core #1 are on the seeds of the totora reed, which occur in abundance in sporadic intervals in the core along with the exoskeletons of an unidentified species of weevil. The other two dates (3880 and 3850 ^{14}C yr BP) are on palm pollen. All the dates from core #2 are on totora seeds. The stratigraphy in core #1 (Fig. 2) reveals a depositional hiatus between 14 and 16 cm corresponding to the time interval 3880 to 830 ^{14}C yr BP (4090–4410 cal yr BP to AD 1180–1290). A similar hiatus exists in core #2 between 18 and 24 cm corresponding to the interval 4320 to 560 ^{14}C yr BP (4640–4970 cal yr BP to AD 1320–1450) (Fig. 3).

Four major sediment types make up the bulk of both cores (Fig. 4). “Coarse detritus” refers to the fibrous, matted remains of aquatic macrophytes—mainly the stems, leaves, and roots of the totora reed. “Fine detritus” refers to spongy masses of plant fragments that lack obvious parting planes related to stems or leaves and yet contain fragments of leaf and stem cuticle that again probably derive mostly from the totora reed. “Gyttja, structureless” refers to soft algal mud, greenish-yellow in color and with a massive structure. “Gyttja, subangular micropeds” refers to subangular fragments of this same algal mud.

The lowest 45 cm in core #1 is mainly coarse detritus with occasional bands of fine detritus and structureless gyttja (Fig. 4). At 50 cm below the water/sediment interface, the subangular

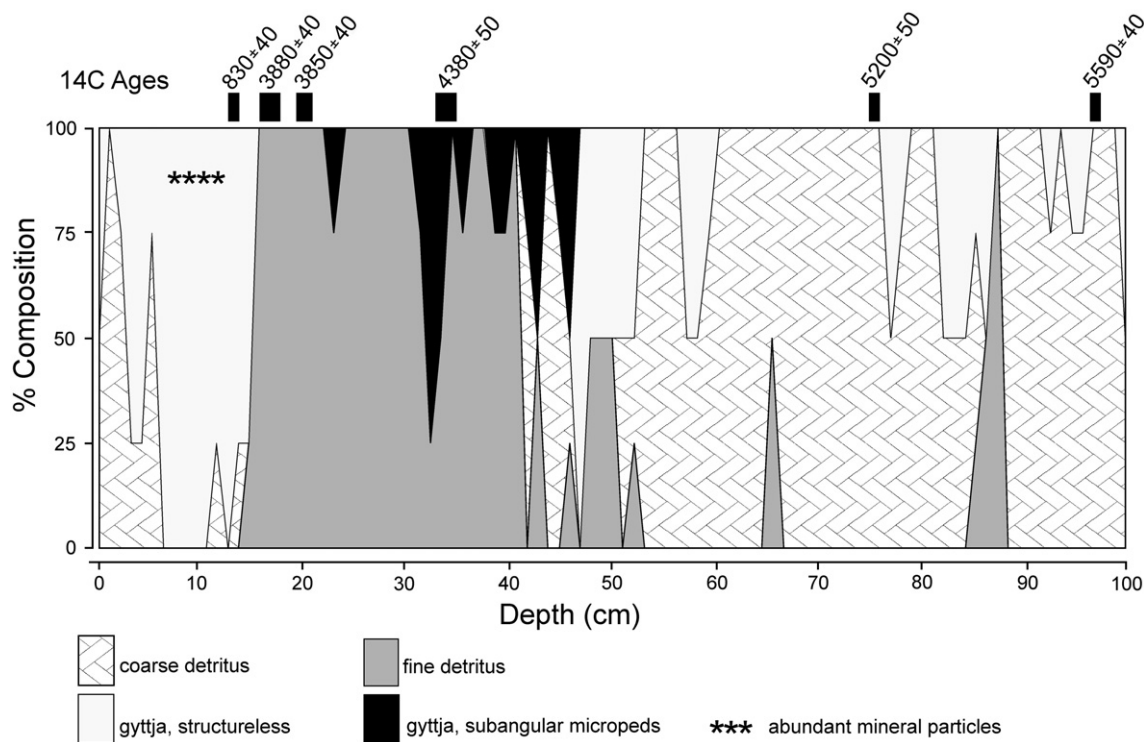


Figure 4. Sediment stratigraphy in Rano Raraku core #1. The alternation of reed detritus and algal mud (gyttja) suggests changes in water depth. The occurrence of subangular fragments of gyttja probably records drying of the lake bed.

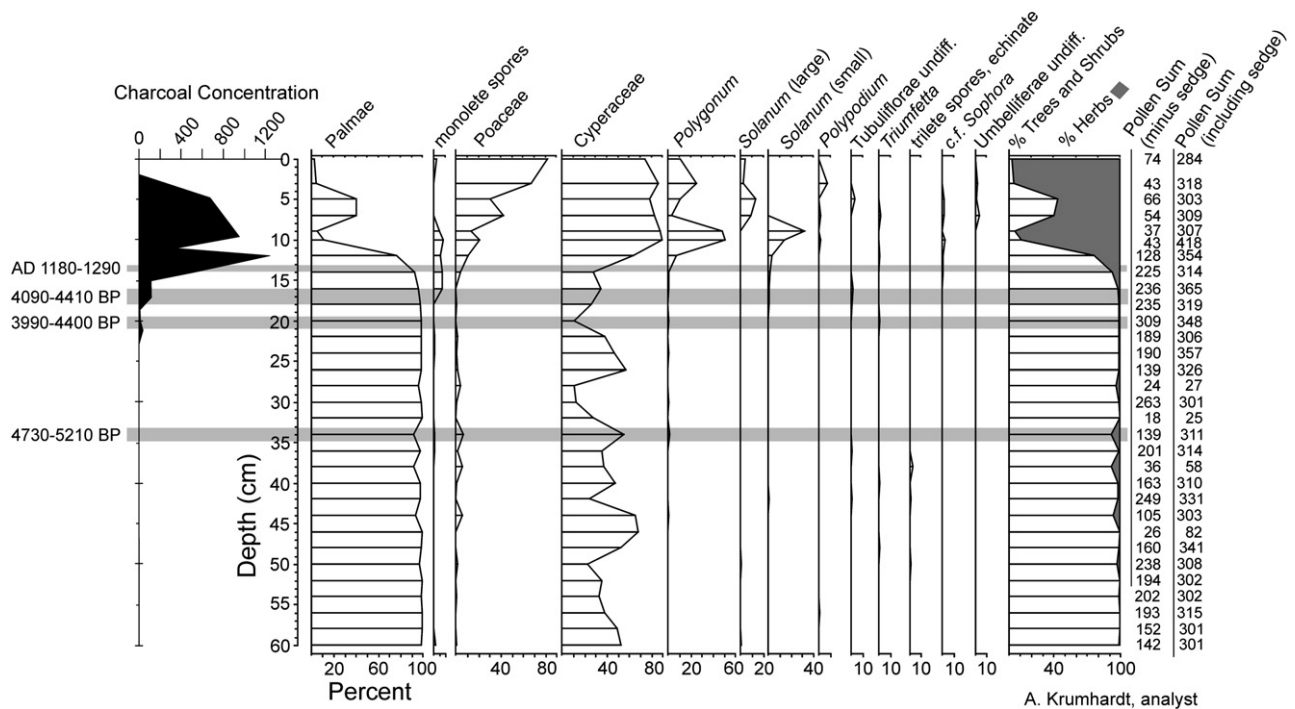


Figure 5. Percentage pollen diagram from Rano Raraku core #1. Leftmost column shows charcoal concentration in the sediment. Dates shown are calibrated ages.

micropeds of gyttja first appear, and fine detritus increases in abundance above 45 cm. An abrupt change occurs around 15 cm where fine detritus is mostly replaced by structureless gyttja. A zone of abundant sand and granules occurs around the 10-cm level. Above this are several concentrations of coarse detritus. The near-surface sediment is structureless gyttja mixed with coarse detritus.

The lower portions of both cores are organic-rich and both cores show a slight decline in percent organic carbon between their bases and levels dating to ca. 4000 ^{14}C yr BP (Figs. 2, 3). In core #1, organic carbon falls sharply between 16 and 14 cm. This decline in C was in progress at 830 ^{14}C yr BP (AD 1180–1290). A similar fluctuating decline in organic C is recorded in core #2 starting sometime after 4320 ^{14}C yr BP (4640–4970 cal yr BP) and was in progress at 560 and 260 ^{14}C yr BP (AD 1320–1450 and AD 1510–1950, respectively). In core #1, magnetic susceptibility rises from low values prior to the drop in organic C to reach a peak sometime after 830 ^{14}C yr BP (AD 1180–1290) around the 10 cm level.

Charcoal is rare below 20 cm in core #1. Only two minor peaks of charcoal occur in sediment, corresponding to the 3880–5590 ^{14}C yr period (4090–6410 cal yr BP). Charcoal begins to increase at the 18-cm level and then increases rapidly above 15 cm. The date of 830 ^{14}C yr BP (AD 1180–1290) falls within the steepest portion of this rise in charcoal abundance (Fig. 2). After reaching several peaks between 4 and 15 cm, charcoal abundance falls to near zero near the core top.

Pollen record

The percentage diagram (Fig. 5) shows that the pre-830 ^{14}C yr BP (AD 1180–1290) pollen flora at Rano Raraku was

dominated by palm and sedge. Grass (Poaceae) was a minor component of the pollen rain, as were trees and shrubs other than palm. Despite concerted looking, pollen and spores are rare at certain levels in the core. Below the 14-cm level, the major changes in the pollen diagram are fluctuations in the percentage of Cyperaceae. Other than sedge, herbaceous taxa are a minor part of the palm-dominated pollen rain.

A striking change occurs around the 14-cm level with palm pollen declining and herbaceous taxa like Poaceae, *Polygonum*, and *Solanum* assuming predominance (Fig. 5). An increase in the percentage of monolete fern spores accompanies the charcoal rise and spans the depositional hiatus in the core. Rapid increases in the percentages of grass, sedge, *Polygonum*, and *Solanum* occur above 14 cm and coincide with the abrupt rise in sedimentary charcoal. A minor peak in palm pollen occurs in the percentage diagram ca. 6 cm.

Discussion

Radiocarbon dating lake and swamp sediments on Rapa Nui

By AMS-dating totora seeds and palm pollen, we obtained stratigraphically consistent ages in cores from Rano Raraku. Other studies have shown that dating bulk sediment samples and unidentified fragments of plant material return inconsistent depth/age profiles (Flenley, 1993a; Peteet et al., 2003; Butler et al., 2004). These inconsistent dates are probably caused by some combination of totora reed mats that overturn (Rano Kau), by reed roots that penetrate deep into older sediment (Rano Aroi), and by in-washing of older carbon from eroding soils in the surrounding watershed (all the crater basins) (Butler et al., 2004). Clearly, totora seeds and palm pollen are the dating

material of choice in future studies of sediment cores from this island.

Timing of forest and soil destruction

The ages of charcoal fragments in colluvial deposits from around the island indicate that forest clearance and attendant soil erosion began on Rapa Nui ca. AD 1200. The deposition of colluvium at many locations between AD 1200 and 1650 implies widespread erosion of the island's primeval soil cover. For this to happen, the existing vegetation cover must have been severely disrupted. The similarity of the oldest charcoal dates from different parts of Rapa Nui suggests that initial forest clearance and soil erosion occurred everywhere on the island within several centuries (Fig. 1). Chronological precision is limited by the errors inherent in the radiometric analysis and by the fact that the ages of the burned plants may pre-date the fire by as much as several centuries (or even more) in the case of trees. Obviously, burning and soil erosion have continued to the present day, but most colluvial charcoal was deposited prior to AD 1700 (Table 1).

The timing of widespread burning indicated by the ages of charcoal fragments in colluvial deposits is corroborated by the timing of the initiation of charcoal deposition in Rano Raraku. Rapid influx of charcoal into Rano Raraku started at the 15-cm level in core #1, which is only a centimeter below the level dating to 830 ± 40 ^{14}C yr BP (AD 1180–1290). Widespread soil erosion was occurring in the Rano Raraku crater at this same time. (Figs. 2, 3). Some of this mineral sediment probably originated from human activities associated with quarrying along the southern rim of the crater. The pollen record indicates that during this pulse of charcoal and mineral material input to the lake, herbaceous species were replacing the pre-existing forest that had been dominated by palm (Fig. 5). Palm pollen continued to be deposited in Rano Raraku above the 10-cm level, suggesting that palm trees survived the initial clearing of the forests, possibly growing around Rano Raraku on steep slopes and cliffs until destroyed by livestock during the 19th century. The association of Polynesian forest clearance with rapid influx of charcoal, widespread soil erosion, and increases in the abundance of grasses, sedges, and certain fern taxa at the expense of trees is well documented on other Pacific islands (e.g., Ellison, 1994; Kirch, 1996; Wilmshurst, 1997; McGlone and Wilmshurst, 1999a; Dodson and Intoh, 1999; Anderson, 2002; Fall, 2005; Kennett et al., 2006).

There are several possible reasons why initial burning had such sudden and radical impacts on soil stability and vegetation cover on Rapa Nui. First, prior to the human use of fire that began ca. AD 1200, Rapa Nui supported a fire-naïve ecosystem (Flenley et al., 1991). Charcoal is rare in the sediments of Rano Raraku during the interval 3880–5590 ^{14}C yr BP (4090–6410 cal yr BP) (Fig. 2). Without a history of frequent fire disturbance, neither soil development nor the composition of the island's vegetation had equilibrated to disturbance by fire. Secondly, Rapa Nui's small size facilitated its rapid burning. Windiness and seasonal droughtiness, combined with a gentle topography devoid of natural firebreaks, probably allowed fires

to spread rapidly. It may not have taken many fire ignitions to burn most parts of this small island, even those distant from the first garden plots that were cleared.

No discernable rat outbreak effect

Hunt (2006, 2007) hypothesizes that an early wave of widespread ecological degradation occurs on newly settled islands because of irruptions of the introduced Pacific rat (kiore, *Rattus exulans*). He speculates that deleterious impacts from these rat outbreaks preceded most human impacts because human populations built up more slowly than rat populations. Rats are known agents of extermination on many islands (Diamond, 1985; Athens et al., 2002; Wilmshurst and Higham, 2004; Towns et al., 2006). Evidence for such a rat outbreak effect would consist of a significant change in the composition of the pollen rain after the date of first human (and rat) arrival on an island but before the first indications of forest burning and soil erosion. We see no evidence for such a rat outbreak effect in the pollen records presented here. That said, it could be that environmental transformation happened too quickly on this small island to be evident in the relatively coarse stratigraphic records now available.

Prehistoric drought

The depositional hiatus in the sediments of Rano Raraku between 830 and 3850 ^{14}C yr BP (1180–3990 cal yr BP) suggests that a drought occurred some time between these limiting ages. Other dated cores from Rano Raraku substantiate the presence of a major depositional hiatus within this basin. In Flenley's cores, the age break occurs between levels dated to 480 ± 60 ^{14}C yr BP (325–550 cal yr BP) (SRR-2425) and 6850 ± 50 ^{14}C yr BP (7520–7740 cal yr BP) (SRR-1553) (Flenley et al., 1991; Flenley, 1993b). In their core from Rano Raraku, Dumont et al. (1998) described a transition from “inorganic silty clay” to “organic silt” (above) at a depth of ~130 cm, and they obtained a date of 590 ± 60 ^{14}C yr BP (500–650 cal yr BP) near this transition on the stem of a *Polygonum* plant. The next, lower date that Dumont et al. (1998) obtained was $16,090 \pm 170$ ^{14}C yr BP (GIF-A-92328) from a depth of 165 cm.

In our cores from Rano Raraku, the subangular micropeds of gyttja in core #1 probably originated from desiccation-cracking of the dry lake bed during this drought. Drying of the lake bed probably also advanced the decomposition state of what was formerly less-decomposed, coarse detritus sediment into the more decomposed, fine detritus sediment. The small increase in charcoal abundance at the 15–20 cm level in core #1 could be the result of charcoal being concentrated out of several millennia's worth of sediment that decayed during this drying episode. This would also explain the approximate 7% decrease in organic C content that we see immediately below the 15-cm level in core #1 (Fig. 2) and similarly just below 20 cm in core #2 (Fig. 3).

It is difficult to think of an explanation for this depositional hiatus other than drought. There is no evidence that early human colonists dug a drainage canal through the crater wall, and the deforestation of the lake's small, closed watershed would

probably have caused an increase rather than a decrease in lake level due to the resultant decline in evapotranspiration. It is possible that fire consumed part of the lake deposit, but for this to happen the lake had to dry out first. It could be that our corer failed to pick up sediment corresponding to the hiatus; however, as just remarked, the same hiatus appears in the cores retrieved by Flenley et al. (1991) using a D-section sampler, and in the one retrieved by Dumont et al. (1998) using a piston corer.

When did this drought or series of droughts end? Algal mud and totora debris were accumulating again at 830 ^{14}C yr BP (AD 1180–1290). Judging from the recent sedimentation rate in the core and based on the fact that only 2 cm separate the 830-yr date from the underlying 3880 date on palm pollen, it seems possible that the lake refilled only decades to several centuries before AD 1180–1290. Polynesian colonists would seem to have begun farming shortly after the end of a major drought.

Are there other droughts recorded in the sediments of Rano Raraku? The post-AD 1180–1290 record is complicated by the influx of material eroded from the crater walls by human activities; however, shifts in the relative abundance of coarse detritus and gyttja in core #1 suggest that significant changes in lake level have occurred during the last 500 yr. A higher resolution core from Rano Raraku is needed to test this idea. Significant fluctuations in lake level prior to 3880 ^{14}C yr BP (4090–4410 cal yr BP) are suggested by changes in sediment types and variations in the percentage values of Cyperaceae and Poaceae pollen (Fig. 5).

Causes and possible regional correlations of droughts on Rapa Nui

Three interacting meteorological phenomena are important in controlling rainfall in the southeast Pacific region today: the ENSO, the subtropical southeast Pacific high, and the tracks taken by the cyclonic storms carried in the westerlies. As mentioned earlier, Genz and Hunt (2003) failed to find any correlation between the ENSO phase and the last 50 yr of precipitation records from Rapa Nui. Nonetheless, the phases of the ENSO do have important effects on precipitation in other parts of the region (McGlone et al., 1992), and it would be surprising if the ENSO did not have some effect on rainfall on Rapa Nui, perhaps on the variance of rainfall at weekly, monthly, or annual time scales. Most of the rain falling on Rapa Nui comes from cyclonic storms moving eastward across the Pacific, and though obscured by high interannual variability, winters tend to be the wettest season there (Genz and Hunt, 2003). For much of the year, Rapa Nui lies beneath the subtropical Pacific high pressure system, which can block the approach of the storms carried in the westerlies (Trenberth, 1991). When the subtropical high weakens or retreats equatorward, cyclonic storms track farther north, reaching southern South America, increasing moisture there and raising lake levels (Kitzberger and Veblen, 2003; Haberzettl et al., 2007a,b). The subtropical high also interacts with the ENSO at middle latitudes in the eastern Pacific. During El Niño phases, a weakened high often accompanies the incursion of moist, tropical air masses and a northward shift in the subtropical

storm track (Solman and Menéndez, 2002). In Chile, the interannual variability of rainfall increases during El Niño years (Markgraf, 1998), occasionally bringing heavy rains to central Chile (Jenny et al., 2002).

Like in southern South America (Markgraf et al., 2003), shifts in the latitude of storm tracks are probably an important trigger for drought on Rapa Nui. Besides shifting on a seasonal basis, storm tracks in the Southern Ocean shift latitudinally depending on the overall pole-equator temperature gradient, which varies at annual, decadal, and millennial time scales according to the Southern Annular Mode (Carleton, 2003). In winter, there are two distinct storm tracks embedded in the westerlies encircling the Southern Hemisphere (Hoskins and Hodges, 2005). The subpolar storm track closely circles Antarctica where it is fed by cyclones forming along the steep temperature gradient between the Southern Ocean and the frozen continent. The subtropical storm track lies farther north where it originates in a zone of sharply contrasting sea-surface temperatures in the southern Indian Ocean. From there it spirals westward, picking up new storms east of Australia and finally merging with the subpolar storm track in the far southern Indian Ocean (Hoskins and Hodges, 2005). Rapa Nui lies near the present-day northern edge of the subtropical storm track in winter (Nakamura and Shimpō, 2004). During summer months, the subtropical storm track weakens, but cyclogenesis continues in a belt that encompasses Rapa Nui and produces weak, westward-moving tropical storm systems (Hoskins and Hodges, 2005).

At first glance, Rapa Nui's extreme geographic isolation would seem to doom the search for correlative climate events elsewhere; however, as just reviewed, rainfall on Rapa Nui is controlled by storm tracks and by the strength of the subtropical high, both of which affect other Southern Hemisphere land areas (Veblen et al., 2003; Markgraf et al., 2003; Mayr et al., 2007). To the southwest in New Zealand, moisture balance changed during the Holocene but in a complex and poorly understood manner (McGlone and Wilmshurst, 1999b; Wilmshurst et al., 2002). Elsewhere in Oceania, the record of Holocene precipitation is fragmentary, though there are suggestions that precipitation increased ca. AD 1300 at the beginning of the Little Ice Age (LIA) (Nunn, 2000; Nunn and Britton, 2001).

More precise proxy records of moisture come from South America where, in southern Patagonia, Haberzettl et al. (2007a, b) find evidence for several episodes of low lake levels, one occurring between AD 1250 and 1410. In northern Patagonia, tree-ring records suggest an episode of cool-moist climate from AD 900 to 1070, followed by warm-dry conditions lasting until AD 1270, after which the cool-moist LIA began (Villalba, 1990, 1994, 1998). Similarly in Tasmania, tree-ring records suggest the occurrence of relatively warm, dry conditions from AD 1100 to 1190 and again, though more briefly, from AD 1475 to 1495 (Cook et al., 1991). Based on the correlation between winter rainfall in central Chile (32–35° S) and tree-ring records in northern Patagonia, Villalba (1994) extends Boninsegna's (1988) record of rainfall in central Chile back to AD 900 and infers the occurrence of a drought there between AD 900 and 1100. Using pollen records, Maldonado and Villagrán (2002) reconstruct changing moisture conditions during the Holocene at

a site at 32° S on the Chilean coast and find evidence for a drought between ca. AD 200 and 700.

In conclusion, latitudinal shifts in the subtropical storm track and resultant changes in the intensity and frequency of cyclonic storms provide a feasible, though untested, climatological trigger for radical changes in moisture balance on Rapa Nui. Based on the geography of the subtropical high pressure system, we might expect synchronous droughts on Rapa Nui and in central Chile, and in fact there is evidence for possible correlative droughts. Looking even farther afield, our minimum-limiting date on the refilling of Rano Raraku ca AD 1180–1290 coincides with the end of a warm, dry climate episode in both northern Patagonia and Tasmania.

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