Journal of Paleolimnology 13: 209–217, 1995.

A Holocene record of climate change, fire ecology and human activity from montane Flat Top Bog, Maui *

D. A. Burney[1], R. V. DeCandido[1], L. P. Burney[1], F. N. Kostel-Hughes[1], T. W. Stafford, Jr.[2] & H. F. James[3]
[1]*Department of Biological Sciences, Fordham University, Bronx, NY 10458, USA*
[2]*Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO 80309-0450, USA*
[3]*MRC NHB 116, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560, USA*

Received 23 May 1994; accepted 11 October 1994

Key words: Hawaii, pollen, fire ecology, trace metals, Trade Wind Inversion, paleoecology

Abstract

A sediment core from a high-elevation bog on Maui in the Hawaiian Islands contains evidence for drier conditions between 9.4–5.8 kyr BP, followed by a wetter interval between 5.8–2.2 kyr BP, and a variable late Holocene. These precipitation changes may be a reflection of vertical displacements of the upper boundary of the mid-Pacific Trade Wind Inversion (TWI) cloud layer. Fires, probably volcanically ignited, occurred in the forests prior to human arrival. Polynesian activity in this high-elevation, remote site was apparently limited, with no pollen, charcoal, or sedimentological evidence for local anthropogenic disturbance. After European contact, grass fires increased and introduced plant species invaded the site. Values for Cd, Cu, Pb, and Zn in sediments throughout the Holocene indicate low trace-metal deposition from atmospheric particulates at the site, even in the twentieth century.

Introduction

The most isolated tropical highlands and rain forests on Earth are found in the middle of the Pacific Ocean on the larger Hawaiian Islands. Despite the biogeographic significance of the diverse endemic biota of these islands, little is known of the Holocene vegetation history or even the broadest outlines of late Quaternary terrestrial paleoclimatic trends.

A palynological investigation was conducted on the islands of Maui, Kauai, and Molokai in the 1940's; however, the prodigious works of Selling (1946, 1947, 1948) predate the advent of ^{14}C dating. As a result, his detailed pollen studies, which document patterns of marked change in some of the first complete pollen diagrams from the tropics, lacked an absolute chronology. Selling believed that some of his longer core sequences were fairly complete postglacial sections. He also inferred that pollen diagrams from several sites showed a consistent three-part division of the Holocene, with a wet period in the middle. This hypothesis has not been tested with dated pollen stratigraphic studies from the Hawaiian Islands.

Athens *et al.* (1992) have produced a dated late Holocene pollen diagram from Kawainui Marsh, a coastal site on Oahu, showing vegetation changes beginning *c.* 1000 A.D., several centuries after the time of initial Polynesian colonization. A rich and well-dated Holocene fossil bone sequence (James *et al.*, 1987) has been recovered from Puu Naio Cave, a low elevation lava tube on East Maui. The cave sediments contain a remarkable extinct avifauna, including bird-catching owls, large flightless waterfowl and a flightless ibis. Other paleontological and archaeological studies (e.g., Christensen & Kirch, 1986; Olson & James, 1984; Athens *et al.*, 1991) have provided a coherent picture of ecological changes during the last two millennia, documenting the collapse of endemic ecosystems through the combined effects of various human impacts on the fauna and vegetation. Similar anthropogenic effects have been demonstrated for other isolated islands, including Polynesia (Kirch *et al.*,

* This paper is one of a series of papers guest edited by Dr. Mark Brenner on tropical paleolimnology

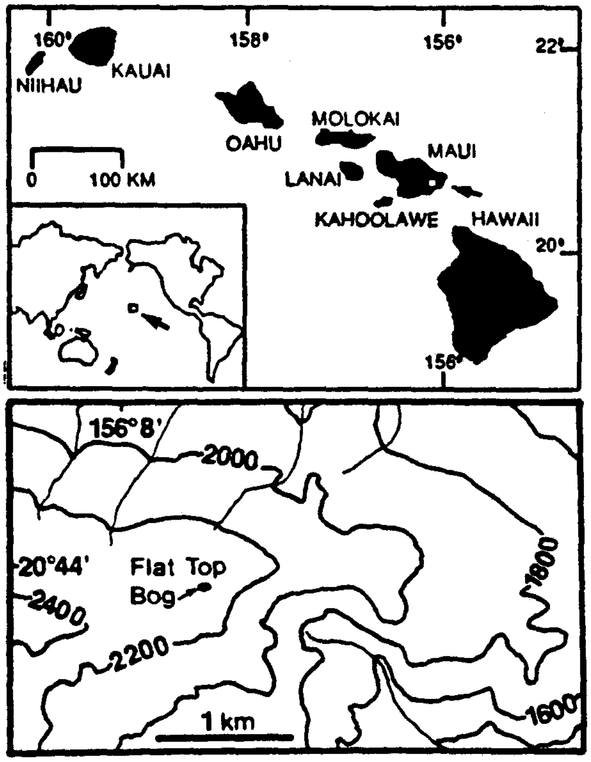

Fig. 1. Location of Flat Top Bog, East Maui. The top of the Trade Wind Inversion cloud zone and the upper extent of rain forest vegetation lie generally between the 1800–2000 m contour intervals (lower inset).

1991), New Zealand (A. Anderson, 1984) and Madagascar (Burney, 1993).

Two types of data severely lacking in the reconstruction of late prehistoric ecosystem dynamics of the Hawaiian Islands are ^{14}C-dated palynological records of vegetation changes of the entire Holocene and fire histories from stratigraphic charcoal analysis. We present evidence of these two types from a high-elevation bog in Haleakala National Park of East Maui (Fig. 1). Our data indicate wetter conditions in the mid-Holocene, possibly caused by an upward displacement of the upper boundary of the cloud layer associated with the mid-Pacific Trade Wind Inversion. Although no definite late Holocene evidence for Polynesian impacts on this high-elevation landscape were detected, we document nearby volcanic activity throughout the Holocene, and European period effects on landscapes of the last two centuries.

The site studied

Flat Top Bog (N20 °44′ W156 °08′) at 2270 m is the highest bog site known from the Hawaiian Islands (Vogl & Henrickson, 1971). Surface-water flow into and out of the bog is restricted. The largely ombrogeneous peat surface encompasses *c.* 1 ha, and is covered by sedges (Cyperaceae) and grasses (Poaceae). The surrounding area is dominated by alpine tussock grasslands containing *Deschampsia nubigena* Hillebr. (Wagner *et al.*, 1990) and, especially in slightly lower ravines nearby, such shrubs as *Coprosma*, *Styphelia*, and *Vaccinium*. On the windward slopes to the east, *Metrosideros/Cibotium* rain forests begin at *c.* 1800–2000 m elevation and extend downslope into lowland vegetation types that are highly altered by human activity and dominated by introduced species. To the west, inside the Haleakala Crater valley, drier leeward formations of grass, shrubs, and Asteraceae predominate.

Methods

A core of 233 cm length was collected from the center of the bog, using a Livingstone piston corer. Sediments were processed for pollen and pteridophyte spores as in Faegri *et al.* (1989). Charcoal particles were analyzed for type (graminoid and non-graminoid) and abundance (projected area in pollen slides) using methods described in Burney (1987) and Patterson *et al.* (1987). Two-step loss on ignition (Dean, 1974) was used to measure organic matter and carbonate content of the sediments.

Concentrations of selected trace metals were measured on a Perkin-Elmer Model 1100B atomic absorption spectrophotometer. Unfiltered sediments for these analyses were processed by acid digestion (J. Anderson, 1974).

Pollen and spore identifications were made by comparison to a large reference collection, housed in the Fordham University Paleoecology Laboratory, of pollen and spore slides prepared from vouchered plant specimens collected in the Hawaiian Islands and elsewhere in the tropics. Photomicrographs and pollen morphological descriptions in Selling (1946, 1947, 1948) were also consulted. The pollen sum is based on total terrestrial pollen and spores. Pollen of Cyperaceae, the primary vegetation on the bog surface, is excluded from the sum. Because grasses dominate the surrounding alpine zone, and tree ferns are a primary component of the rain forests below, Poaceae pollen

Table 1. ^{14}C dates from the Flat Top Bog core

Lab #	Core interval	^{14}C age[1]	Fraction
Beta-49840	75-80 cm	2190 ± 70	peat[2]
Beta-50689	116-120 cm	2730 ± 100	peat
CAMS-3489	166-170 cm	5450 ± 70	humins[3]
CAMS-3488	166-170 cm	5790 ± 70	humic acids[4]
CAMS-3490	171-175 cm	5750 ± 70	humins
CAMS-3545 Beta-55062	206-210 cm	9380 ± 70	humins

[1] In radiocarbon years BP, corrected for isotopic fractionation and reported with 1σ. Samples reported with a CAMS number are AMS dates determined in the accelerator facilities at Lawrence Livermore National Laboratories. Others are conventional (beta-counting) dates from Beta Analytic, Inc. CAMS-3545 was pretreated by Beta Analytic, Inc.
[2] 'Peat' dates were bulk sediment samples pretreated with HCl to remove carbonates.
[3] 'Humins' were extracted from bulk sediments by pretreatment with HCl to remove carbonates, and KOH to remove humic and fulvic acids.
[4] 'Humic acids' were extracted for dating by using HCl to precipitate humic acids from the supernatant of the CAMS-3489 KOH treatment.

and pteridophyte spores could not be excluded from the pollen sum without greatly reducing the information content of the pollen percentages.

Pollen zonation was carried out using CONISS (constrained incremental sum-of-squares) on the terrestrial pollen and spore data (including all taxa $\geq 2\%$ in at least one sample) using Orloci's Chord Distance as the dissimilarity coefficient (Overpeck *et al.*, 1985). Diagrams were plotted on TILIA software developed by Eric Grimm (Illinois State Museum).

Results and discussion

Radiocarbon dating and sediment description

Six ^{14}C dates (Table 1) were obtained, including a basal AMS ^{14}C age of 9380±70 yr BP (CAMS-3545) on the sediment humin fraction from 206–210 cm. Deeper coring was stopped by a hard clay mixed with basaltic gravel, which was recovered in the bottom 6 cm of the core. From 227 to 193 cm the sediment is comprised of dusky-red (10R 3/3) fine silt with some fine volcanic ash (<60 μm), with organic matter increasing to almost 40% at 193 cm. High organic matter and low carbonate content (carbonates throughout the core are <5%) also characterize the dark reddish-brown (5YR 3/4) sandy silty clay unit between 193–175 cm. Near the top of this unit, abundant diatom frustules, mostly of *Pinnularia lata* (Breb.) Wm. Sm., are present. A black, fine-grained peat (10YR 2/1) is found in the core from 175–158 cm, becoming dark reddish-brown (2.5YR 2.5/3) near the top of the unit. AMS ^{14}C dates on the humin fraction of this unit yielded ages of 5750±70 (CAMS-3490) and 5450±70 (CAMS-3489) for the intervals 171–175 cm and 166–170 cm respectively. Sedimentary humic acids were extracted and dated separately for the 166–170 cm layer, yielding an age of 5790±70 yr BP (CAMS-3488), close agreement for the mobile organic fraction. This multiple-dating approach increases confidence in the chronology for this key part of the core.

From 158 to 121 cm, the pollen-bearing organic sequence is interrupted by a dusky red (10R 3/3) tephra consisting of fine ash with dark red (10R 3/6) cinders to 5 mm. Above the tephra, from 120 to 101 cm, there is a very dusky red (2.5YR 2.5/2) fibrous peat. A conventional ^{14}C date of 2730±100 yr BP on peat at 116–120 cm (Beta-50689) suggests up to 2000 yr of sediments were either (1) removed by erosion or not deposited, (2) compressed into the *c.* 10 cm of dense peat packed between the previous date (5450 yr BP) and the ash layer, or (3) mixed with the ash layer by water, roots or other processes. Based on the *c.* 20% organic matter of the upper part of the ash layer, scenario (3) seems probable, although not mutually exclusive of the other two effects. The uniform lithology of the tephra (no weathering horizons except at the top of the layer) suggests it was deposited by a single volcanic event, or closely-timed events.

The dusky red fibrous peat is overlain by a finer, highly organic (to 98% dry weight) black (5YR 2.5/1) peat that continues up to 20 cm. A conventional peat ^{14}C date from the 75–80 cm interval *c.* 20 cm above the color change in the peat yielded an age of 2190±70 yr BP (Beta-49840). The top 20 cm of the core is dark reddish-brown (2.5YR 2.5/4) silty peat. At 18 cm there is a distinct thin lamina of pumice.

Pollen analysis

The pollen diagram (Fig. 2) shows the changes in terrestrial pollen spectra over the last *c.* 9400 ^{14}C yr. CONISS identifies three distinct pollen zones. Zone 1, the basal portion of the core, contains grass pollen (Poaceae) comprising 63.5–86.4% of the sum of total terrestrial pollen and spores. *Dubautia* complex pollen

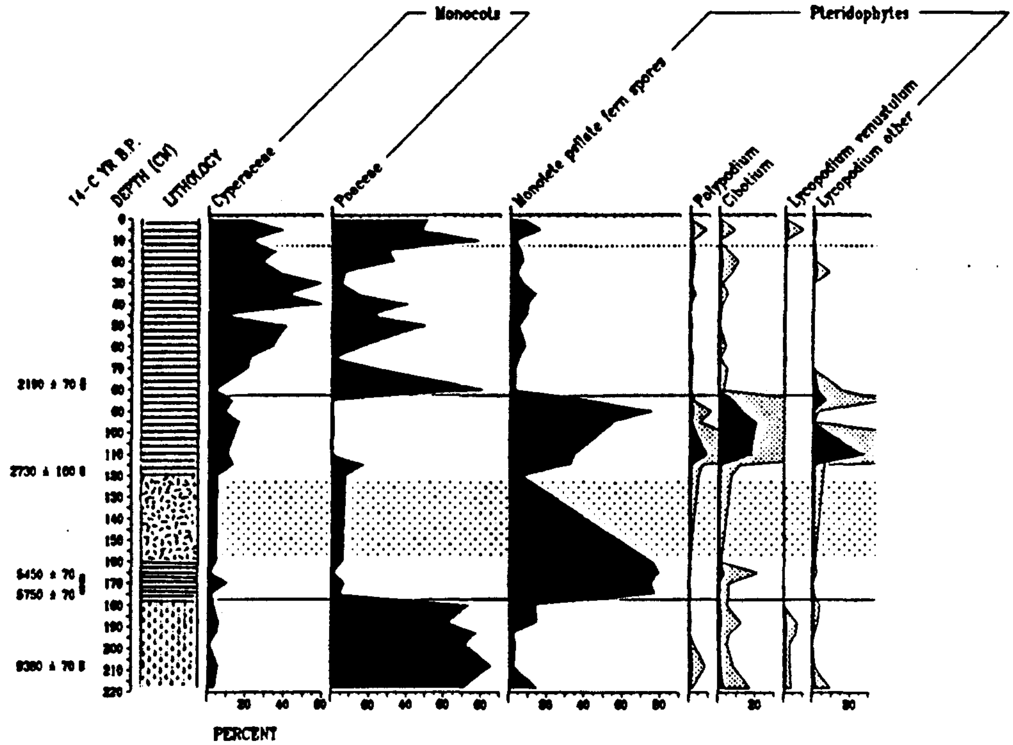

Fig. 2. Pollen diagram for Flat Top Bog. Pollen sum is based on total terrestrial pollen and spores. Pollen of Cyperaceae, the primary vegetation on the bog surface. is excluded from the sum. Grey shading indicates 5 × exaggeration of pollen percentages. Zonation is based on constrained incremental sum-of-squares clustering (CONISS), using Orloci's Chord Distance as the dissimilarity coefficient.

is present at values ranging up to 16.7% in the mid-portion of the zone. This generalized pollen type (Selling, 1947) is produced by not only *Dubautia*, a genus that includes woody species, but also several other Hawaiian Asteraceae, including *Argyroxiphium*, the montane silverswords and greenswords characteristic of the high elevations of Haleakala National Park. Other tree and shrub pollen types, Cyperaceae, and pteridophyte spores occur at generally lower percentages in this pollen zone than in the other two zones. The plant assemblage inferred for the highly uniform pollen spectra of Zone 1 is that of a relatively dry alpine grass/Asteraceae community similar to that found today on drier slopes at high elevations.

Zone 2, beginning at the level dated 5750±70 yr BP, is characterized by a sharp decline in Poaceae pollen to <8%, except at the 115 cm level (18%) which overlies a thick ashfall in the middle portion of this zone. Zone 2, except for the spectra immediately above the tephra, is dominated by pteridophytes, including tree ferns (*Cibotium*), *Polypodium*, several *Lycopodium* species, and many monolete psilate types, probably including the bush-sized woody fern *Sadleria*. Low CONISS values prior to the ashfall (Zone 2-A), indicating highly similar pollen spectra, contrast with the rather dissimilar spectra following (Zone 2-B). This high dissimilarity is most likely a reflection of the successional character of the vegetation that colonized the site after one or more volcanic eruptions. As noted above, it is also possible that up to 2000 yr of the sedimentary record is missing or obscured in the interval between *c.* 3–5 kyr BP, since the inception of Zone 2-B dated to 2730±100 yr BP.

The general trend in Zone 2-B is from initially high values for *Coprosma* and *Myrsine* to an increase in *Cibotium* and other pteridophyte spores, low Poaceae, and moderate values for *Cheirodendron* and other mesic types. Taken with the Zone 2-A spectra, the overall trend is for much wetter conditions than in Zone 1, interrupted by pyroclastic deposition at the site sometime between 5-3 kyr BP.

Zone 3, a collection of rather dissimilar pollen spectra, begins with a rapid decline of pteridophyte spores and a rise of Poaceae to >80%. A peat ^{14}C date from the 75–80 cm interval at the inception of this zone yielded an age of 2190±70 yr BP. Subsequent pollen spectra in

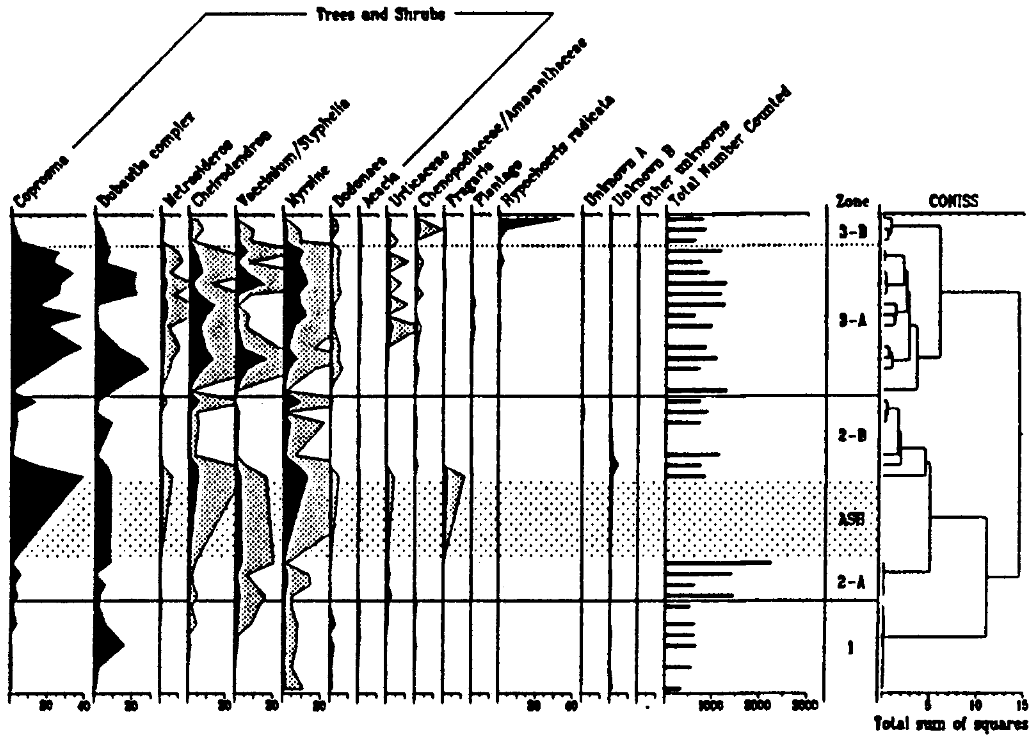

Fig. 2. Continued.

this peat zone are highly erratic, with dominance shifting back and forth between Poaceae, Cyperaceae, and various tree and shrub taxa. Although most of these spectra fall within the period of Polynesian settlement, thought to have begun about 300–400 AD or slightly earlier (Hunt & Holsen, 1991), no definitive evidence is seen in the pollen spectra for human impacts in this remote high-elevation site. The relatively high values for such potentially ruderal herbs as Urticaceae, Chenopodiaceae/Amaranthaceae, and *Plantago* could be evidence for periodic human disturbance, but there is no consistent trend toward more degraded forms of vegetation as one would expect if human impacts were accelerating with indigenous population increase and agricultural expansion inland and upslope. High elevation areas such as this are not very suitable for the tropical crops grown by the Polynesians. In addition, all these taxa are represented in the indigenous flora by species (e.g., *Urera glabra* (Hook & Arnott) Wedd., *Chenopodium oahuense* (Meyen) Aellen and *Plantago pachyphylla* A. Gray) that show no definite connection with human disturbance (Wagner *et al.*, 1990). Vegetation shifts associated with the Medieval Climate Optimum and Little Ice Age may possibly explain these variations, but the low sedimentation rate at this site in the late Holocene (*c.* 70 cm in the last 2 kyr) precludes accurate delineation of such short-term climatic trends.

Zone 3-B, beginning *c.* 10 cm below the modern surface, clearly reflects European contact, with the advent of pollen of a naturalized plant introduced by Europeans, hairy cats-ear (*Hypochoeris radicata* L.), which reaches 33.5% in this sub-zone, undoubtedly representing the sediments that have accumulated since European arrival in the late 18th century. This plant grows presently on the bog surface as well as in the surrounding alpine grasslands. The presence of a few grains of this type in the adjacent samples of the uppermost sub-zone 3-A confirm that the present bog surface has been mixed downward, probably through such exotic agencies as feral pigs and earthworms, both introduced to Hawaii by humans and documented sources of bog surface disturbance on Haleakala (Medeiros *et al.*, 1991).

Charcoal analysis

The charcoal stratigraphy of the Flat Top Bog core (Fig. 3) shows evidence for fire activity in the region throughout the Holocene. Although microscopic charcoal particles were present at all levels examined, the consistently highest values occurred in the post-European contact period of the last two centuries, probably as a reflection of the widespread practice of controlled burning of lowland sugar-cane fields during this time interval. The period prior to *c.* 5 kyr BP was also characterized by high values at some levels. We employed a technique developed in previous studies (e.g., Burney, 1987) to microscopically distinguish charcoal derived from graminoid sources and 'other' charcoal, fibrous and amorphous types derived primarily from trees and shrubs. These charcoal analyses show that charcoal of the last two centuries was derived primarily from grasses, whereas the high charcoal values at some early-to-mid-Holocene levels was primarily non-graminoid, suggesting fires in forested areas. It is probable that these carbon particles were dispersed from volcano-ignited fires in the montane forests. There is no way to rule out the possibility of lightning-caused fires as well, although the prevalence of pyroclastics in the associated sediments, especially prior to *c.* 3 kyr BP, indicates a probable volcanic origin for most fires. The Haleakala volcanic vents are thought to have been active throughout the Holocene with the last small eruption recorded by oral tradition in the 18th century (Macdonald *et al.*, 1970). The pyroclastic layer at 18 cm may represent this event.

Although some studies on other isolated islands have documented major increases in charcoal at about the time of human arrival (e.g., Burney, 1987, 1993; Burney *et al.*, 1994), the charcoal record of this core shows no detectable increase in charcoal during Polynesian times. Some of the lowest values of the core are recorded in this period, providing indirect confirmation of the negative evidence from unpublished archaeological surveys that the Flat Top Bog area has never been inhabited by Polynesians (A. C. Medeiros, pers. comm.).

Trace metals

We measured the surface adsorbed and precipitated concentrations of four metals in the core sediments (Fig. 4) whose airborne levels have global environmental significance. Cd, Cu, Pb, and Zn concentrations were relatively low throughout the core (cf. range of values in Tab. 21.3 of Berglund, 1986), confirming the conclusions from high-elevation background air particle monitoring studies on Mauna Loa (Parrington, 1984) that the high-altitude air over the mid-Pacific is extremely pure, showing little or no evidence for trace-metal inputs from industrial processes. Only Pb showed a slight increase in the surficial (late 20th century) samples from the bog. Highest overall values for this metal, however, were from the early and mid-Holocene. Zn and Cu showed mid-Holocene maxima, and Cd is low throughout.

These patterns provide no evidence for increased base-cation leaching or particulate saltation from potentially disturbed soils during the Polynesian period, when many of the lowest values were recorded, supporting the conclusion from pollen and charcoal data that Polynesian disturbance of this high-elevation locality was minimal. The slightly elevated values for three of the four metals earlier in the Holocene are probably a reflection of the locally high levels of volcanic activity in the vicinity (highest values for all metals measured were from the pyroclastic-dominated section of the core). The inferred increase in local precipitation for the mid-Holocene may also have contributed to the higher trace metal values, either through increased run-off from the bog rim or through the formation of condensation nuclei around metal-bearing particulates. Base-cation leaching from the bog rim may well have occurred at the inception of Pollen Zone 2 in particular, since the presence of periphytic diatoms in the fine-grained organic sediments indicates surface water accumulation at the site. These indirect forms of evidence agree with the more direct pollen data indicating that the site was wetter in the mid-Holocene, perhaps reflecting an upward shift in the TWI cloud zone.

The Trade Wind Inversion

The mid-Pacific TWI is a consequence of the vast stable high pressure system of the subtropical Pacific Anticyclone. This temperature inversion layer separates dry air above from moist air below, with the upper boundary in the Hawaiian Islands generally below 2000 m at present (Jones, 1939; Selling, 1948; Porter, 1979). At Haleakala (L. Loope, pers. comm.) this corresponds approximately to the separation of the *Deschampsia* grassland and *Vaccinium/Coprosma* shrubland above (precipitation <2500 mm yr^{-1}) from the *Metrosideros/Cibotium* tree fern rain forest below (precipitation 5000–10,000 mm yr^{-1}) (Leuschner &

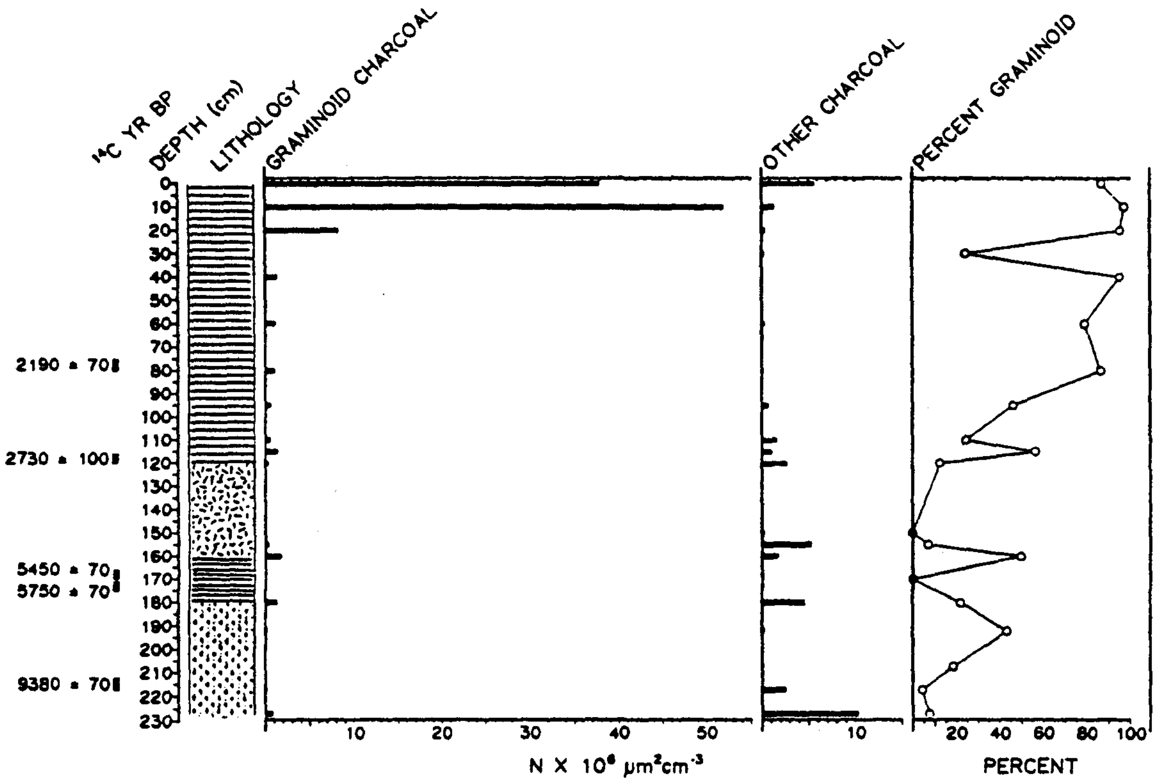

Fig. 3. Concentrations of graminoid and all other forms of microscopic charcoal from Flat Top Bog core, in terms of projected area in pollen slides. Column on right gives percent of all charcoal identified as graminoid.

Schulte, 1991). Between 5.8–2.2 kyr, the rain forest apparently moved up the mountain to surround Flat Top Bog. Whether this reflects a higher upper boundary for the TWI in mid-Holocene times, or a fundamentally different pressure and precipitation regime in the Hawaiian highlands at this time cannot be determined from this study; however, a two to four-fold increase in precipitation is indicated. Well-dated sequences for the entire Holocene from mid- and low-elevation sites will help resolve this question, as well as clarifying the extent of Polynesian modification of the more arable and accessible portions of the Hawaiian Islands.

The results of this study suggest that Selling (1948) was generally correct in his supposition that his longer high-elevation cores, showing three pollen zones (the middle one indicating wetter conditions), reflected a three-part division of high-elevation Holocene climate in the mid-Pacific. We propose that his zones I, II, and III for the Puu Kukui cores on West Maui in particular (various sites ranging from 1375–1750 m elevation) generally correspond to our pollen zones 1, 2, and 3 respectively. Direct transference of our dates for the zone transitions would not be prudent, however. Only re-analysis of his sites, with careful radiocarbon dating, could fully confirm or refute the observed similarity. Also, since Puu Kukui is presently within the TWI, a mid-Holocene wet phase there indicates an increase in precipitation, but gives no direct clue as to whether the inversion layer also extended above the present-day 2000 m limit.

Acknowledgments

We thank L. L. Loope, A. C. Medeiros and R. Nagata of Haleakala National Park for assistance with logistics. L. L. Loope and A. C. Medeiros provided valuable comments on the manuscript. A. C. Medeiros, A. Goetz and J. Hume helped with the coring. This work was supported by the Smithsonian Scholarly Studies Program, the National Science Foundation (BSR-9025020), Fordham University Faculty Research Grants, the Routh Summer Fellowships program of the Louis Calder Center, the US National Park

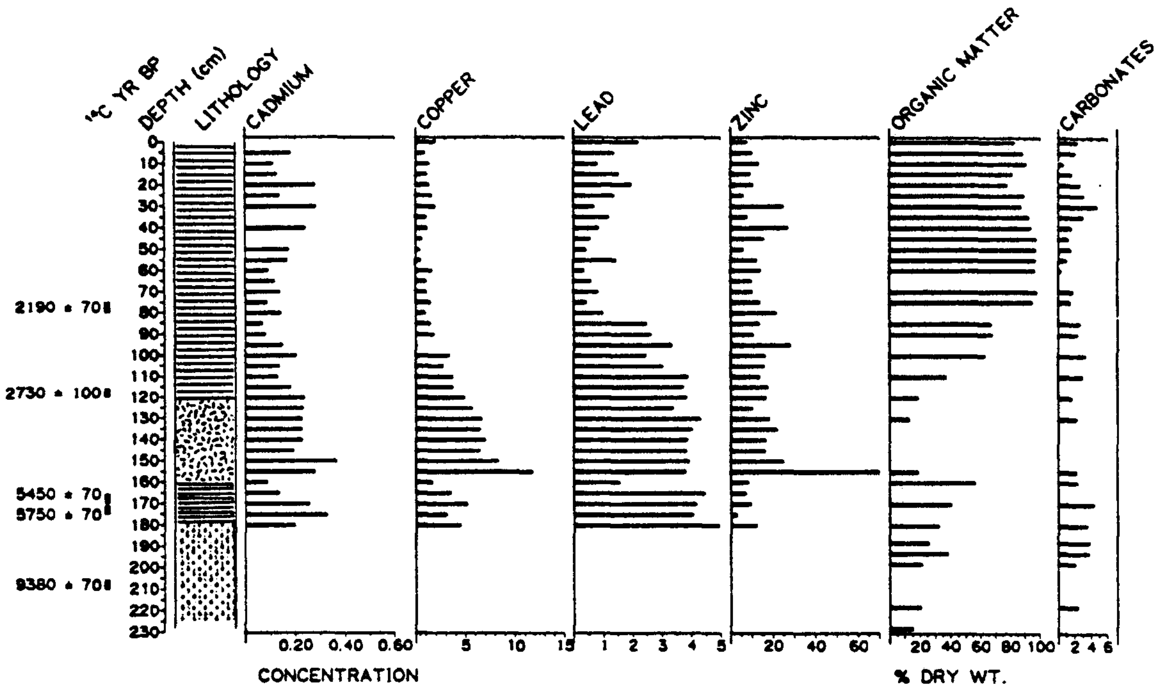

Fig. 4. Surface adsorbed and precipitated concentrations of selected trace metals from Flat Top Bog core, expressed in $\mu g\ g^{-1}$. No trace metals were measured below 180 cm depth because of the small amount of sediment available. Also shown are percent dry weight of organic matter and carbonates.

Service, the Torrey Botanical Club and the Hawaii Audubon Society.

References

Anderson, A., 1984. The extinction of moa in southern New Zealand. In P. S. Martin & R. G. Klein (eds.), Quaternary extinctions: a prehistoric revolution. Univ. Arizona Press, Tucson: 728–740.

Anderson, J., 1974. A study of the digestion of sediment by the HNO_3-H_2SO_4 and the HNO_3-HCl procedures. Atomic Absorption Newsletter 13: 31–32.

Athens, J. S., M. W. Kaschko & H. F. James, 1991. Prehistoric bird hunters: high altitude resource exploitation on Hawai'i Island. Bishop Mus. Occas. Pap. 31: 63–84.

Athens, J. S. J. V. Ward & S. Wickler, 1992. Late Holocene lowland vegetation, O'ahu, Hawai'i. New Zealand J. Archaeol. 14: 9–34.

Berglund, B. E. (ed.), 1986. Handbook of Holocene palaeoecology and palaeohydrology. Wiley, Chichester, 869 pp.

Burney, D. A., 1987. Late Quaternary stratigraphic charcoal records from Madagascar. Quat. Res. 28: 274–280.

Burney, D. A., 1993. Late Holocene environmental changes in arid southwestern Madagascar. Quat. Res. 40: 98–106.

Burney, D. A., L. P. Burney & R. D. E. MacPhee, 1994. Holocene charcoal stratigraphy from Laguna Tortuguero, Puerto Rico, and the timing of human arrival on the island. J. Archaeol. Sci. 21: 273–281.

Christensen, C. C. & P. V. Kirch, 1986. Nonmarine mollusks and ecological change at Barbers Point, O'ahu, Hawai'i. Bishop Mus. Occas. Pap. 26: 52–80.

Dean, W. E., Jr., 1974. Determinations of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. J. Sediment. Petrol. 44: 242–248.

Faegri, K., P. E. Kaland & K. Krzywinski, 1989. Textbook of pollen analysis, IV ed. Wiley, Chichester, 328 pp.

Hunt, T. L. & R. M. Holsen, 1991. An early radiocarbon chronology for the Hawaiian Islands; a preliminary analysis. Asian Perspectives 30: 147–161.

James, H. F., T. W. Stafford, Jr., D. W. Steadman, S. L. Olson, P. S. Martin, A. J. T. Jull & P. C. McCoy, 1987. Radiocarbon dates on bones of extinct birds from Hawaii. Proc. Nat. Acad. Sci. USA 84: 2350–2354.

Jones, S. B., 1939. The weather element in Hawaiian climate. Ann. Ass. Amer. Geogr. XXIX.

Kirch, P. V., J. R. Flenley & D. W. Steadman, 1991. A radiocarbon chronology for human-induced environmental change on Mangaia, southern Cook Islands, Polynesia. Radiocarbon 33: 317–328.

Leuschner, C. & M. Schulte, 1991. Microclimatological investigations in the tropical alpine scrub of Maui, Hawaii: evidence of a drought-induced alpine timberline. Pacific Science 45: 152–168.

Loope, L. L., A. C. Medeiros & B. H. Gagne, 1991. Aspects of the history and biology of the montane bogs of Haleakala National Park. Cooperative Nat. Pk. Resources Studies Unit, Univ. Hawaii/Manoa, Dept. Botany Tech. Rept. 76: 43 pp.

Macdonald, G. A., A. T. Abbott & F. L. Peterson, 1970. Volcanoes in the sea. U. Hawaii Press, Honolulu, 517 pp.

Olson, S. L. & H. F. James, 1984. The role of Polynesians in the extinction of the avifauna of the Hawaiian Islands. In P. S. Martin & R. G. Klein (eds.), Quaternary extinctions: a prehistoric revolution. Univ. Arizona Press, Tucson: 768–780.

Overpeck, J. T., T. Webb III & I. C. Prentice, 1985. Quantitative interpretation of fossil pollen spectra: dissimilarity coefficients and the method of modern analogs. Quat. Res. 23: 87–108.

Parrington, J. R., 1984. The chemistry of background atmospheric particles collected at Mauna Loa Observatory, Hawaii. Ph.D. dissertation. U. of Maryland, College Park, 60 pp.

Patterson, W. A., III, K. J. Edwards & D. J. MacGuire, 1984. Microscopic charcoal as a fossil indicator of fire. Quat. Sci. Rev. 6: 3–23.

Porter, S. C., 1979. Hawaiian glacial ages. Quat. Res. 12: 161–187.

Selling, O. H., 1946. Studies in Hawaiian pollen statistics, part I. The spores of the Hawaiian pteridophytes. Bishop Mus. Spec. Pub. 37: 87 pp.

Selling, O. H., 1947. Studies in Hawaiian pollen statistics, part II. The pollens of the Hawaiian phanerogams. Bishop Mus. Spec. Pub. 38: 430 pp.

Selling, O. H., 1948. Studies in Hawaiian pollen statistics, part III. On the Late Quaternary history of the Hawaiian vegetation. Bishop Mus. Spec. Pub. 39: 154 pp.

Vogl, R. J. & J. Henrickson, 1971. Vegetation of an alpine bog on East Maui, Hawaii. Pacific Science 25: 475–483.

Wagner, W. L., D. R. Herbst & S. H. Sohmer, 1990. Manual of the flowering plants of Hawaii. Bishop Mus. Spec. Pub. 83: 1853 pp.