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LATE HOLOCENE ^{14}C MARINE RESERVOIR CORRECTIONS FOR HAWAI‘I DERIVED FROM U-SERIES DATED ARCHAEOLOGICAL CORAL

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ABSTRACT. The first application of U-series dating and accelerator mass spectrometry (AMS) assay of Polynesian archaeological *Pocillopora* spp. branch corals for deriving a precise local marine reservoir correction (ΔR) is described. Known-age corals were selected that spanned the entire culture-historical sequence for the Hawaiian Islands, thus eliminating the problem of not having known-age dated samples that cover the period of direct relevance to prehistorians; in this case, about AD 700–1800. Dating coral samples from windward and leeward coastlines of Moloka‘i Island, with different offshore conditions such as upwelling, currents, wind patterns, coastal topography, and straight or embayed shorelines, provides insights into possible variations of local conditions on the same island—something that has never been attempted. In this regard, there was no spatial variability in ΔR during the 17th century. We report a weighted average ΔR value for Moloka‘i Island of 52 ± 25 yr using 12 pair-dated dedicatory branch corals from religious archaeological sites and demonstrate that there is no significant temporal variability in ΔR between about AD 700 to 1800. In combination with 4 selected previously published ΔR values based on pre-bomb known-age marine shells, a revised ΔR of 66 ± 54 yr is established for the Hawaiian Islands. However, future research should examine the archipelago-wide spatial variability in ΔR with the analysis of additional dated archaeological coral samples.

INTRODUCTION

Accurate dating is fundamental to building culture-historical chronologies worldwide. Radiocarbon is the most common method used in the Pacific, while the first applications of U-series dating of Polynesian archaeological materials was initiated just recently (Kirch and Sharp 2005; Weisler et al. 2006; McCoy et al. 2009). Aside from careful sample selection to ensure that the dated material clearly relates to the archaeological event (Dean 1978), a fundamental problem with ^{14}C chronologies built on charcoal dates is the possibility of inbuilt age of wood samples. Significant inbuilt age, common in long-lived tree species, can add hundreds of years to the true age of the archaeological event. Until recently, inbuilt age was only shown to be an important problem in New Zealand archaeology where trees can live for hundreds of years (Salmon 1980:30; McFadgen et al. 1994). However, Allen and Wallace (2007) have demonstrated that tropical Polynesian trees, especially the widespread *Cordia subcordata*, which has a maximum reported age >100 yr, can add significant inbuilt age that has a marked effect on interpreting archaeological events. While we advocate identification of wood charcoal to taxon and selection of short-lived taxa for dating, we also recognize that this can be a costly process, there are few people with the necessary skills to identify wood to taxon, and accurate identifications to the genus and, especially, the species level are problematic in the dry leeward areas of Hawai‘i where most of the indigenous vegetation is long destroyed (Athens 1997) and voucher species for building reference collections are in short supply.

Marine shell is commonly used in New Zealand to build archaeological chronologies (McFadgen et al. 1994) and marine fish shows promise as a reliable dating material (Petchey 1998, 2000). Marine shell is common in most Polynesian archaeological sites and is especially important when it is the only dating material for determining the chronology of coastal geomorphic events (e.g. Beggerly 1990). Marine shell is generally easy for most archaeologists to identify to taxon with reference books. Furthermore, in a recent dating study of New Zealand archaeological sites, Schmidt (2000:i) found that charcoal dates are “less reproducible than marine shell” probably due to wood inbuilt age.

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Materials composed of carbon ultimately derived from the dissolved inorganic carbon (DIC) pool (all marine materials, and also terrestrial animals with an appreciable marine-derived diet), require the determination of the local marine reservoir correction (or ΔR) for a proper calibration of their ^{14}C ages. The ΔR value accounts for local/regional ^{14}C offsets from the global ^{14}C marine reservoir ages, which are due to variations in ocean circulation (e.g. vertical mixing as upwelling and horizontal advection), variability in air-sea exchange of CO_2 and variations in influences by local freshwater run-off.

Just 20 yr ago, only 3 ΔR values for the entire tropical Pacific were available (Stuiver et al. 1986: Table 1). The most recent marine reservoir correction database contains 97 individual ΔR values for the Pacific (Reimer and Reimer 2003) and we agree with Dye (1994) that some of these assays are of questionable value due to the species of the sample material and its environmental context.

Paired samples of wood charcoal and marine shell from presumably well-defined stratigraphic contexts have been used to derive a marine reservoir correction, although "… the temporal relationship between paired samples is not so precisely defined as for the known-age case" (Jones et al. 2007: 95). In this regard, site disturbance processes must be clearly identified (Wood and Johnson 1978) as typical Polynesian shell middens evidence disturbance from prehistoric excavation of ovens, pits, and postholes, which displace cultural materials within and between layers (Kirch and McCoy 2007: 394; Khaweerat el al. 2008).

ΔR has also been calculated by ^{14}C dating of known-age marine shells collected prior to 1950, so-called pre-bomb material (Phelan 1999; Petchey et al. 2004; Soares and Dias 2006). However, essential information on museum specimens, which were used for the determination of ΔR, was not always sufficient. For example, in some cases, the environmental context where the specimens were collected is unknown and/or the specimens were presumably collected alive (Southon et al. 2002; Hua et al. 2004), thereby putting the accuracy of ΔR determined by this method into question. ^{14}C analyses of annually banded corals spanning the pre-bomb period were also employed for estimating ΔR (Dang et al. 2004; Hua et al. 2004; Reimer and Reimer 2003; Southon et al. 2002). However, these 2 methods only provide data points for ΔR during the past century or two, prior to 1950; that is, after the time that prehistorians are interested in dating marine-derived and affected materials from archaeological sites and geomorphic contexts. These problems are solved by accelerator mass spectrometry (AMS) ^{14}C analysis of known-age corals where they have been dated by the U-series technique (Cao et al. 2007; Yu et al. 2006; McGregor et al. 2008).

In this paper, we describe the first application of U-series dating and AMS assay of archaeological *Pocillopora* spp. corals to derive a precise ΔR for Moloka‘i Island for the period AD 700–1800. We selected known-age corals that spanned the entire culture-historical sequence for the Hawaiian Islands, thus eliminating the problem of not having known-age dated samples that cover the period of direct relevance to prehistorians. A precise reservoir correction permits accurate calibration of other archaeological marine samples such as fish, turtle and sea bird bones, and urchins and contributes to more accurately dating bones of terrestrial animals with a significant marine diet. This could include, for example, rats, pigs, dogs, chickens, and humans—many of which are commonly recovered from Polynesian archaeological contexts.

STUDY AREA AND METHODS

Study Area and Sample Selection

Our study area is the western third of Moloka‘i Island (Hawaiian Archipelago) where extensive archaeological surveys and excavations have been conducted over the 20,000-hectare region during the past 20 yr (Weisler 1989, 1990; Weisler et al. 2006). This leeward settlement pattern consists of prehistoric habitations clustered around embayments where many residential complexes contain a freestanding stone structure known ethnographically as a fishing shrine (*ko'a*)—a structure where fresh branch coral ("stones") were placed as ritual offerings (Handy 1927; Malo 1951; Weisler et al. 2006) and incorporated into subsurface deposits. We have obtained high-precision TIMS U-series dates (with 2-σ uncertainty of only ± 2–8 yr) on >160 coral samples from well-provenanced stratigraphic contexts, spanning AD 700–1800 in ~200-yr increments where possible. Twelve U-series dated coral samples were selected for AMS ^{14}C analysis to investigate possible spatial and temporal variation in ΔR.

Two samples were dated from each of the 3 coastlines of west Moloka'i: (1) northern, windward, basalt boulder coast with a steep drop-off; (2) southern, leeward shoreline with raised beachrock, basalt boulder hardshore, sandy beaches, and a barrier reef ~1 km offshore; and (3) a western coast with a basalt boulder shoreline punctuated by sandy embayments (Figure 1). All 6 of these samples yielded U-series dates in the 17th century. Dating coral samples from different coastlines with different characteristics in upwelling, currents, wind patterns, and offshore topography provides insights into possible variations of local conditions on the same island—something that has never been attempted. To document any temporal change in ΔR, we also selected from an archaeological site on the south coast, near the west end of Moloka'i, 6 additional U-series dated corals that spanned ~AD 700 to 1800, thus bracketing well before colonization of the Hawaiian Islands and into the protohistoric period (McCoy 2007; Weisler 1989).

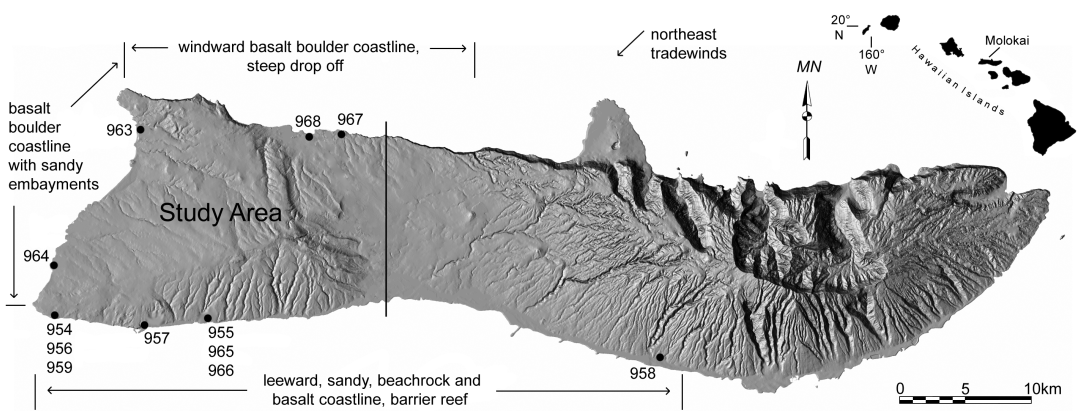

Figure 1 Map of the Hawaiian Archipelago and Moloka'i Island showing the main study area, the characteristics of the coastlines, and locations of dated archaeological coral reported in this study.

Some 3100 coral samples weighing 46.85 kg were collected by Weisler from archaeological sites along the 3 coastlines of west Moloka'i. We specifically selected *Pocillopora* spp. corals for dating, but <5% of the assemblage consisted of branching species of *Porites*. The species composition of the corals from archaeological sites along each coast mirrored the diversity of *Pocillopora* coral species offshore. This was probably due to 2 reasons. First, the Hawaiian Islands have only 40 species of reef-building corals belonging to 16 genera (Maragos 1977:161), which, as a group, is considered a depauperate fauna within the Indo-Pacific region (Grigg 1983:1). In marked contrast, 60 genera are known from the southwest Pacific (see Stoddart 1992: Figure 14). There are only 5 species of *Pocillopora* in Hawai'i, one of which (*P. molokensis*) is rare (Maragos 1977:217) and *P. damicornis* is less common (Jokiel et al. 2008:45). Although the remaining 3 taxa have slightly different habitat preferences (e.g. optimum depth, protected bays, wave-agitated environments), all 3 taxa, in roughly the same concentrations, are found along the 3 coastlines of our study area. Second, the species inventory of all archaeological sites combined for each coastline suggests an opportunistic strategy for acquiring dedicatory corals during prehistory. Although we acknowledge that 2 dedicatory corals were carried ~45 km inland to shrines near the summit of Mauna Kea, Hawai‘i Island (McCoy et al. 2009), there is no archaeological or ethnohistoric evidence of ritual corals being moved from one source area (coastline) to another. Thus, it is likely that archaeological corals in our study area represent species obtained from the adjacent shorelines and are appropriate samples for examining the spatial variability in ΔR from the 3 different coastlines.

Prior to dating, <1-g coral samples were powdered and analyzed for calcite content by X-ray defraction at the Centre for Microscopy and Microanalysis, University of Queensland. No calcite was identified in any of the coral samples, which were, in all cases, unaltered from original mineralogy (aragonite) and suitable for U-series and AMS dating.

U-Series Dating

Detailed analytical procedures for dating recent corals are described in Yu et al. (2006) and Weisler et al. (2006). Fresh coral chips, free of any weathered surfaces, were cut from each of the coral samples, cleaned ultrasonically, and spiked with a ^{229}Th–^{233}U–^{236}U mixed tracer. After total dissolution in nitric acid, concentrated hydrogen peroxide was added to decompose any organic matter and to ensure complete mixing between the spike and the sample. U and Th were coprecipitated with iron hydroxide, and then redissolved in nitric acid prior to purification using standard anion-exchange methods. The U and Th fractions were loaded onto individual, pretreated zone-refined rhenium filaments and sandwiched between 2 graphite layers. The U and Th isotope signals were measured separately as ^{232}Th/^{229}Th, ^{229}Th/^{230}Th, ^{233}U/^{235}U, ^{234}U/^{235}U, and ^{233}U/^{236}U ratios by thermal ionization mass spectrometry (TIMS) at the University of Queensland. The ^{230}Th/^{238}U and ^{234}U/^{238}U activity ratios were then calculated based on these measurements, and the known spike isotopic compositions and decay constants from Cheng et al. (2000). ^{230}Th ages were then calculated using the Isoplot EX 2.3 program of Ludwig (1999) and are reported in Table 1.

In Table 1, 2 corrected ^{230}Th ages were reported, one assuming the non-radiogenic ^{230}Th/^{232}Th ratio = $4.4 \pm 2.2 \times 10^{-6}$ (bulk-earth value), and the other assuming the non-radiogenic ^{230}Th/^{232}Th ratio = $1.4 \pm 0.7 \times 10^{-5}$ (determined from a modern coral at Kahikinui, Maui, next to Moloka‘i Island [Kirch and Sharp 2005]). As all the dated coral samples are of very high purity, containing only 0.027–0.128 ppb Th, the non-radiogenic ^{230}Th contribution is insignificant and the correction on the ^{230}Th ages are insensitive to the choice of the 2 different assumptions. The resulting difference between the 2 types of corrected ^{230}Th ages is <3 yr, which is ~50 times smaller than the 2-σ ranges of the AMS ^{14}C dates. Recent studies (e.g. Cobb et al. 2003; Shen et al. 2008) reveal significant variations in the non-radiogenic ^{230}Th/^{232}Th ratios in modern corals from Pacific Ocean settings, but nevertheless all the determined values in the 2 studies are $<2.4 \times 10^{-5}$, with most $<1 \times 10^{-5}$. In this study, it is probably more reasonable to use the corrected ^{230}Th Age-II for the calculation of ΔR values in Table 2, mainly because the non-radiogenic ^{230}Th/^{232}Th value used for calculating the corrected ^{230}Th age was directly measured from live coral from the vicinity. Nevertheless, we note that the choice of age correction models has little impact on either the calculated ΔR values or our main conclusion of this study.

Table 1 U-Th isotope data and ages for selected *Pocillopora* branching coral samples from archaeological sites.[a]

Sample name	U (ppm)	^{232}Th (ppb)	(^{230}Th/^{232}Th)	(^{230}Th/^{238}U)	(^{234}U/^{238}U)	uncorr. ^{230}Th age (AD)	corr. ^{230}Th Age-I (AD)	corr. ^{230}Th Age-II (AD)	Initial δ^{234}U	Year of analysis
38-07	2.7496 ± 0.0023	0.066 ± 0.000	411 ± 05	0.003267 ± 0.000027	1.1455 ± 0.0016	1694 ± 3	1695 ± 3	1696 ± 3	144.0 ± 1.6	2005
52-04	2.8131 ± 0.0040	0.066 ± 0.000	418 ± 06	0.003230 ± 0.000036	1.1491 ± 0.0014	1701 ± 3	1701 ± 3	1703 ± 4	147.7 ± 1.4	2007
821-2	2.2815 ± 0.0024	0.026 ± 0.000	849 ± 11	0.003180 ± 0.000037	1.1496 ± 0.0013	1705 ± 4	1705 ± 4	1706 ± 4	148.2 ± 1.3	2006
821-S2/5-7	2.5782 ± 0.0021	0.050 ± 0.000	500 ± 08	0.003212 ± 0.000036	1.1501 ± 0.0009	1703 ± 3	1703 ± 3	1704 ± 3	148.6 ± 0.9	2007
MW001	2.7270 ± 0.0026	0.035 ± 0.000	987 ± 13	0.004216 ± 0.000033	1.1462 ± 0.0014	1604 ± 3	1605 ± 3	1605 ± 3	144.8 ± 1.4	2005
MW010	2.9142 ± 0.0028	0.027 ± 0.000	1302 ± 14	0.004048 ± 0.000018	1.1471 ± 0.0014	1621 ± 2	1621 ± 2	1621 ± 2	145.6 ± 1.4	2005
B5-60-4C	2.4562 ± 0.0029	0.128 ± 0.000	395 ± 04	0.006767 ± 0.000062	1.1493 ± 0.0014	1365 ± 6	1366 ± 6	1369 ± 6	147.9 ± 1.4	2007
821-S2/3-3	2.6731 ± 0.0039	0.050 ± 0.000	383 ± 05	0.002371 ± 0.000022	1.1496 ± 0.0017	1781 ± 2	1782 ± 2	1783 ± 2	148.1 ± 1.7	2006
B5-60-2	2.5843 ± 0.0022	0.059 ± 0.000	1813 ± 18	0.013661 ± 0.000063	1.1489 ± 0.0010	706 ± 6	707 ± 6	708 ± 6	147.9 ± 1.1	2007
Walter-2	2.5304 ± 0.0025	0.052 ± 0.000	857 ± 12	0.005756 ± 0.000037	1.1497 ± 0.0011	1460 ± 4	1461 ± 4	1462 ± 4	148.3 ± 1.1	2006
006-6	2.3855 ± 0.0017	0.125 ± 0.001	267 ± 04	0.004606 ± 0.000051	1.1461 ± 0.0009	1567 ± 5	1568 ± 5	1571 ± 5	144.7 ± 0.9	2005
B5-60-4B	2.5803 ± 0.0030	0.088 ± 0.001	852 ± 18	0.009607 ± 0.000082	1.1539 ± 0.0014	1098 ± 8	1099 ± 8	1101 ± 8	152.7 ± 1.4	2007

[a]Note: Errors are quoted at 2 σ. Ratios in parentheses refer to activity ratios, calculated using decay constants from Cheng et al. (2000). All ages were calculated using the Isoplot EX 2.3 program of Ludwig (1999). Uncorrected age was calculated assuming no non-radiogenic ^{230}Th, whereas corrected age I and II, assuming $^{230}Th_{nr}/^{232}Th$ atomic ratio of 4.4 ± 2.2 × 10^{-6} (bulk-earth value), and 1.4 ± 0.7 × 10^{-5} (determined from a modern coral at Kahikinui, Maui [Kirch and Sharp 2005]). See Yu et al. (2006) and Weisler et al. (2006) for detailed analytical procedures. Corrected ^{230}Th Age-II was used for the calculation of ΔR, although the choice of Age-I and Age-II make virtually little difference in the calculated ΔR values or our interpretation of the data.

Table 2 ^{14}C results and ΔR values for Moloka‘i Island, Hawaiian Archipelago, derived from U-series dated corals.

Lab nr	Sample ID	Location	$\delta^{13}C$ (‰)	Conventional ^{14}C ages ±1 σ (BP)	U-Th ages ±2 σ (cal AD)	Model marine ages ±1 σ (BP)[a]	ΔR ±1 σ (^{14}C yr)[b]
OZJ963	38-07	West coast	–2.2	626 ± 36	1696 ± 3	587 ± 5	39 ± 36
OZJ964	52-04	West coast	–2.0	641 ± 41	1703 ± 4	577 ± 5	64 ± 42
OZJ965	821-2	South coast	–2.5	575 ± 42	1706 ± 4	567 ± 5	8 ± 42
OZJ966	821-S2/5-7	South coast	–1.8	601 ± 39	1704 ± 3	572 ± 5	29 ± 39
OZJ967	MW001	North coast	–2.7	772 ± 36	1605 ± 3	714 ± 5	58 ± 36
OZJ968	MW010	North coast	–2.2	768 ± 37	1621 ± 2	712 ± 5	56 ± 37
OZK954	B5-60-4C	South coast	–3.8	1113 ± 53	1369 ± 6	998 ± 5	115 ± 53
OZK955	821-S2/3-3	South coast	–2.7	608 ± 49	1783 ± 2	535 ± 5	73 ± 49
OZK956	B5-60-2	South coast	–3.2	1723 ± 53	708 ± 6	1667 ± 5	56 ± 53
OZK957	Walter-2	South coast	–1.9	927 ± 50	1462 ± 4	858 ± 5	69 ± 51
OZK958	006-6	South coast	–2.7	759 ± 55	1571 ± 5	725 ± 5	34 ± 55
OZK959	B5-60-4B	South coast	–3.2	1351 ± 53	1101 ± 8	1294 ± 5	57 ± 53

[a]Model marine age and uncertainty were estimated using the method described in Owen (2002). These values were chosen so that when they were calibrated using CALIB program version 5.0.1 (Stuiver et al. 2005), Marine04 data set (Hughen et al. 2004) and ΔR = 0, their associated calibrated (or U-Th) age range, showed in the previous column, was produced.

[b]ΔR was calculated using Equation 1. Its associated 1-σ uncertainty is $(\sigma_{\text{Measured age}}^2 + \sigma_{\text{Model age}}^2)^{1/2}$.

AMS ^{14}C Analysis

For each coral, 4–5 annual growth bands were collected for ^{14}C analysis. This strategy aimed to avoid possible large seasonal/annual variability in surface ocean ^{14}C (Druffel et al. 2001; Guilderson et al. 2004; Hua et al. 2005), which may influence the result of our study. A subsection of each coral containing 4–5 annual bands was cut along the growth axis using a diamond saw. The samples were then cleaned with deionized (Milli-Q) water in an ultrasonic bath several times for 20 min each to remove any surface contamination. They were dried in an oven at 60 °C for 2 days. Dried coral samples were mechanically homogenized using mortar and pestle before hydrolysis. The cleaned samples were hydrolyzed to CO_2 using 85% phosphoric acid and then converted to graphite using the H_2/Fe method (Hua et al. 2001). A small portion of graphite from each sample was employed for the determination of $\delta^{13}C$ using the Micromass IsoPrime EA/IRMS. The remaining graphite of each sample was loaded into an aluminum cathode by rear pressing for ^{14}C analysis. AMS measurements were carried out using the STAR facility at ANSTO (Fink et al. 2004). The AMS ^{14}C ages of these corals are reported in Table 2.

RESULTS AND DISCUSSION

A ΔR at location *x* and time *t* is defined as:

$$\Delta R\ (x,t) = \text{measured marine } ^{14}C \text{ age } (x,t) - \text{model marine } ^{14}C \text{ age } (t) \quad (1)$$

where measured marine ^{14}C age (x,t) is the conventional ^{14}C age of coral shown in column 5 of Table 2, and model marine ^{14}C age (t) represents the ^{14}C age of the global surface oceans reported in the Marine04 data set (Hughen et al. 2004), presented in column 7 of Table 2. It is worth noting that for the last 10,500 yr the model marine ^{14}C age reflects the response of the global ocean mixed-layer to changes in atmospheric ^{14}C production calculated by a box-diffusion model (Hughen et al. 2004). ΔR values for Moloka‘i Island for the period AD 700–1800 derived from dated corals are reported in the last column of Table 2 and illustrated in Figure 2. Our results indicate: (1) no spatial variability in ΔR during the 17th century is observed because ΔR values for the north, south, and west coasts of Moloka'i Island are identical within 1-σ error; and (2) there are no significant variations in ΔR for the study period AD 700–1800 as all values overlap each other within 1-σ error. The weighted average ΔR value based on the ^{14}C analytical error for Moloka'i Island is 52 ± 25 ^{14}C yr, where the uncertainty is 1-σ standard deviation. This allows us to use the above average ΔR to calibrate ^{14}C ages of marine samples, and bones of terrestrial animals with a significant marine diet, for the entire culture-historical sequence of Moloka'i Island between AD 700 and 1800 (Figure 2).

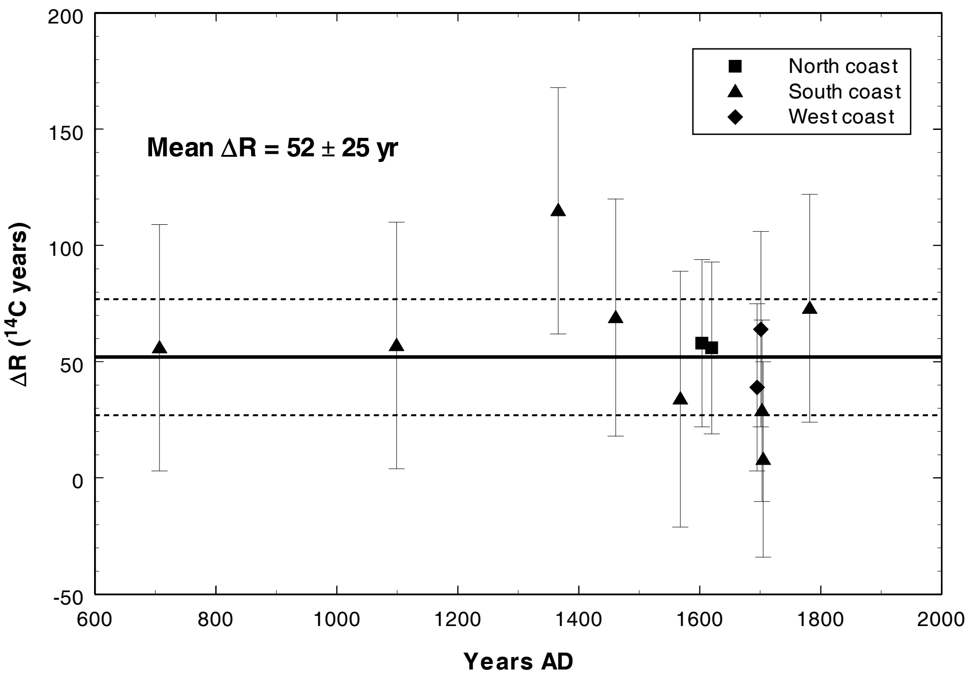

Figure 2 Spatial and temporal variability in ΔR of Moloka'i Island during AD 700–1800

Druffel et al. (2001) measured ^{14}C in annually banded corals from the western Kona coast of the Big Island of Hawai'i. We converted these published annual ^{14}C values to ΔR values. The weighted average of ΔR during the period AD 1893–1949 (n = 60) is –34 ± 27 yr. This value is insignificantly lower than our average value for Moloka'i of 52 ± 25 yr for AD 700–1800. However, the western Kona coast is known for large local groundwater discharge with 31 major point-source discharge plumes (surface area >13,000 m^2) along ~100 km of coastline (Johnson et al. 2008). As the ^{14}C content in DIC of local groundwater may not be similar to that of surface ocean, the above coral ΔR value may be influenced by local groundwater discharge and is not used for the calculation of the weighted mean ΔR for Hawai'i, which is discussed later.

There were ~25 individual ΔR values previously published for Hawai'i, which are based on pre-bomb known-age shells, and paired charcoal and shell in the same layer of archaeological sites (Broecker and Olson 1961; Athens 1985; Beggerly 1990; Dye 1994). The validity of these values was comprehensively discussed by Dye (1994). Selected previously published ΔR values derived from pre-bomb known age shells, which may be reliable according to the evaluation of Dye (1994), are presented in Table 3. Large variations in ΔR values in Table 3 from –39 ± 64 to 289 ± 103 yr may

Table 3 Selected previously published ΔR values for Hawai‘i based on pre-bomb known-age shells.

Lab nr	Shell species	Location	Collection year	Conventional ^{14}C ages ±1 σ (BP)	Model marine ages ±1 σ (BP)[a]	ΔR ±1 σ (^{14}C yr)[b]	References
Moloka‘i Island							
Beta-12903	*Tellina palatam*	Puko‘o	1905	410 ± 60	449 ± 23	–39 ± 64[c]	Athens (1985)
O‘ahu Island							
L-576J	*Trechus intertextus*	O‘ahu	1840	629 ± 50	490 ± 23	139 ± 55	Broecker and Olson (1961)
Beta-15793	*Tellina palatam*	Pearl Harbor	1927	430 ± 60	451 ± 23	–21 ± 64[c]	Beggerly (1990)
Beta-15794	*Conus distans*	Kane‘ohe Bay	1947	510 ± 60	464 ± 23	46 ± 64[c]	Beggerly (1990)
Beta-14024	*Tellina palatam*	Waikane	1925	680 ± 40	451 ± 23	229 ± 46[c]	Athens (1985)
Hawai‘i Island							
Beta-54336	*Cellana exarata*	Kaulana	1923	740 ± 100	451 ± 23	289 ± 103	Dye (1994)
Beta-54334	*Cypraea caputserpentis*	Kaulana	1923	730 ± 80	451 ± 23	279 ± 83	Dye (1994)
Beta-54335	*Nerita picea*	Kea‘au	1924	610 ± 80	451 ± 23	159 ± 83	Dye (1994)

[a]Model marine age is Marine04 data set (Hughen et al. 2004).
[b]ΔR was calculated using Equation 1.
[c]ΔR was not used for the calculation of the average ΔR value for Hawai‘i (see text for discussion).

indicate huge spatial variability in ΔR for the Hawaiian Islands, which is in contrast with the result of our study for Moloka'i. Alternatively, some of these shell samples may not be appropriate for the determination of ΔR.

Our results for Moloka'i Island are insignificantly different from the ΔR value of –39 ± 64 yr for the south coast of Moloka'i (Beta-12903), determined by Athens (1985) using a sample of tellen shell (*Tellina palatam*), as this value overlaps with most of our ΔR values within 1-σ uncertainty except samples OZJ965, OZJ967, OZK954, and OZK955. However, *Tellina palatam* tolerates silty sand inshore environments (Kay 1979:563) and the dated tellen shell was obtained from "sandy mud" (Athens 1985:89) at Puko'o, along the south shore of Moloka'i. Freshwater run-off (mainly rainfall), which is especially pronounced at Puko'o, may also influence its ΔR because the ^{14}C content in rainwater DIC is usually higher than that of surface ocean.[4] Similar effects can be expected for a tellen shell collected at Pearl Harbor (Beta-15793), where freshwater run-off is high. Another tellen shell from Waikane fishpond (Beta-14024) may be influenced by springs as prehistoric fishponds were often located near springs (Summers 1964). Potential problems can also occur when samples are obtained from lagoons, estuaries, and bays, whose waters do not represent open-ocean water due to limited exchange between these reservoirs and open surface ocean. A *Conus distans* shell collected at Kane'ohe Bay, O'ahu (Beta-15794) is 1 example of this case. Therefore, ΔR values derived from the above 4 shell samples are not included in the estimation of the average ΔR for Hawai'i.

We calculated the Hawai'i archipelago-wide ΔR by including our coral samples and 4 marine shells in Table 3 that do not inhabit inshore areas with high run-off, are often found in bays, or associated with springs or estuaries. As mentioned previously, we did not include the coral ΔR value from the western Kona coast, which may be influenced by local groundwater discharge, into our weighted mean estimate for Hawai'i. While this may have eliminated some useful values, we have erred on the side of caution. Our revised weighted average ΔR value for Hawai'i is 66 ± 54 yr.

CONCLUSIONS

1. Using 12 pair-dated U-series and AMS-dated *Pocillopora* spp. branch coral samples from archaeological sites, we have

- observed no spatial variations in ΔR for Moloka'i Island, at least for the 17th century;
- found no significant temporal variations in ΔR for Moloka'i Island for the period AD 700–1800;
- established a weighted average ΔR for Moloka'i Island of 52 ± 25 yr.

2. The weighted average ΔR for Hawai'i, which is based on 4 selected previously published ΔR values in Table 3 and our 12 values for Moloka'i Island, is 66 ± 54 yr. This value is revised from a previous ΔR of 115 ± 50 for the Hawaiian Islands (Stuiver and Braziunas 1993: Figure 16).

3. This is an improved method for documenting the spatial and temporal variability in the ΔR for Moloka'i Island—which is especially relevant to dating archaeological sites with marine samples and bones of terrestrial animals with a significant marine diet. Our protocol can be expanded to include other islands of Hawai'i and other archipelagos in East Polynesia where coral was incorporated into ritual architecture and household shrines (Weisler et al. 2006: Figure1).

[4]It is worth noting that our coral samples from the south coast of Moloka'i presented in this paper (see Table 2) were collected near the west end of the island. These samples are located far away from Puko'o (10–30 km) and other freshwater sources and therefore not influenced by freshwater run-off.

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APPENDIX

The results of AMS analyses for 12 dedicatory corals collected from religious archaeological sites on west Moloka'i Island, Hawaiian Archipelago are presented. AMS measurements were carried out using the STAR facility at ANSTO (Fink et al. 2004). Calibrations were made using CALIB 5.01 (Stuiver et al. 2005) using the Marine04 data (Hughen et al. 2004), with a ΔR of 52 ± 25. Each archaeological site number, reported here, is prefaced by 50-60 in accordance with the State Historic Preservation Office system or Mo (i.e. Moloka'i) for Bishop Museum site numbers. The weight of each dated coral specimen is reported, not the portion used for AMS analysis. See Tables 1 and 2 for corresponding AMS and U-series dates. The results are grouped by coast, then by increasing lab number.

North Coast

$\delta^{13}C = -2.7‰$

OZJ967Anahaki Gulch area **772 ± 36 BP**

Pocillopora meandrina branch coral (100.3 g) from archaeological site 01-16C. This temple (*heiau*) is a square enclosure with 2 attached stone-filled terraces forming the largest structure in the area (Weisler et al. 2006: Figure 1) with a commanding view to the west. The dedicatory coral (field object 1) was collected from excavation unit N3W3, spit 2 at 10 cm below surface. Collected on 20 January 1999 by MIW and submitted by MIW on 9 May 2007.

Comment: cal AD 1495–1671 (2 σ), 100% probability; cal AD 1538–1640 (1 σ), 100% probability.

$\delta^{13}C = -2.2‰$

OZJ968 Moomomi **768 ± 37 BP**

Pocillopora sp. branch coral (114.3 g) from archaeological site 01-242, a coastal midden with buried shrine. The dedicatory coral (field object 4) was collected from excavation unit N26W6, layer IIIB, spit 6, 50 cm below surface (Weisler et al. 2006: Figure 2). Collected on 28 January 1999 by MIW and submitted by MIW on 9 May 2007.

Comment: cal AD 1476–1697 (2 σ), 100% probability; cal AD 1536–1657 (1 σ), 100% probability.

West Coast

$\delta^{13}C = -2.2‰$

OZJ963 Kawakiu Nui **626 ± 36 BP**

Pocillopora sp. branch coral (68.3 g) from archaeological site 01-38. A rectangular stone enclosure interpreted as a men's house (*hale mua*). The dated dedicatory coral was collected from the surface on the northeast corner of the small pavement (altar) in the north, interior end of the structure (Summers 1971:47–8, Figure 11; Weisler 1987: Figure 8). Collected on 21 June 2005 by MIW and submitted by MIW on 9 May 2007.

Comment: cal AD 1649–1884 (2 σ), 100% probability; cal AD 1683–1776 (1 σ), 81% probability.

$\delta^{13}C$ = –2.0‰

OZJ964 Kaupoa area **641 ± 41 BP**

Pocillopora sp. branch coral (43.9 g) from archaeological site B6-66. A rectangular stone enclosure with a raised pavement (altar) along the entire interior inland (east) side (Summers 1971:53); the site may have functioned as a men's house. This dedicatory coral was collected from the surface of the pavement, at the north end, ~50 cm from the north wall. Collected on 21 June 2005 by MIW and submitted by MIW on 9 May 2007.

Comment: cal AD 1620–1889 (2 σ), 100% probability; cal AD 1669–1772 (1 σ), 86% probability.

South Coast

$\delta^{13}C$ = –2.5‰

OZJ965 near Kahinawai Gulch **575 ± 42 BP**

Pocillopora meandrina branch coral (100.2 g) from archaeological site 01-821. A high-status residential complex consisting of a high-walled nearly square enclosure with attached shrine. The dedicatory coral was collected from the surface of the shrine pavement (altar), in the southwest corner. Collected on 26 June 2005 by MIW and submitted by MIW on 9 May 2007.

Comment: cal AD 1690–1908 (2 σ), 92% probability; cal AD 1707–1858 (1 σ), 100% probability.

$\delta^{13}C$ = –1.8‰

OZJ966 near Kahinawai Gulch **601 ± 39 BP**

Pocillopora sp. branch coral (31.0 g) from archaeological site 01-821. A high-status residential complex consisting of a high-walled enclosure with attached shrine. The dedicatory coral (field object 7) was collected from shrine excavation unit 2, layer II, spit 3,18 cm below surface. Collected on 17 December 2005 by MIW and submitted by MIW on 9 May 2007.

Comment: cal AD 1669–1899 (2 σ), 98% probability; cal AD 1694–1821 (1 σ), 100% probability.

$\delta^{13}C$ = –3.8‰

OZK954 Keawakalani **1113 ± 53 BP**

Pocillopora sp. branch coral (7.2 g) from archaeological site B5-60 (01-60). A stone platform situated near the cliff edge, it is interpreted as a fishing shrine or *ko'a* (Summers 1971:55). The dedicatory coral was collected from the northwest corner of the structure. Collected on 26 January 2007 by MIW and submitted by MIW on 12 May 2008.

Comment: cal AD 1229–1425 (2 σ), 100% probability; cal AD 1282–1360 (1 σ), 84% probability.

$\delta^{13}C$ = –2.7‰

OZK955 near Kahinawai Gulch **608 ± 49 BP**

Pocillopora sp. branch coral (23.8 g) from archaeological site 01-821. A high-status residential complex consisting of a high-walled enclosure with attached shrine. The dedicatory coral was collected from shrine excavation unit 2, layer II, spit 3, 15 cm below surface. Collected on 16 December 2005 by MIW and submitted by MIW on 12 May 2008.

Comment: cal AD 1658–1904 (2 σ), 96% probability; cal AD 1684–1825 (1 σ), 100% probability.

$\delta^{13}C$ = –3.2‰
OZK956 Keawakalani 1723 ± 53 BP
Pocillopora sp. branch coral (22.1 g) from archaeological site B5-60 (01-60). A stone platform situated near the cliff edge, it is interpreted as a fishing shrine or *ko'a* (Summers 1971:55). The dedicatory coral was collected on 26 January 2007 by MIW and submitted by MIW on 12 May 2008.

Comment: cal AD 617–863 (2 σ), 100% probability; cal AD 668–779 (1 σ), 100% probability.

$\delta^{13}C$ = –1.9‰
OZK957 east of Haleolono Point 927 ± 50 BP
Pocillopora sp. branch coral (56.5 g) from archaeological site 01-71. A "modified outcrop" consisting of stones placed between outcrops to form a level surface. Situated near the edge of the cliff with commanding views of the coastline, the structure is interpreted as a fishing shrine. The dedicatory coral was collected from the surface of the stone-filled, level area. Collected on 25 June 2005 by MIW and submitted by MIW on 12 May 2008.

Comment: cal AD 1336–1548 (2 σ), 100% probability; cal AD 1415–1498 (1 σ), 100% probability.

$\delta^{13}C$ = –2.7‰
OZK958 Kawela 759 ± 55 BP
Pocillopora ligulata branch coral (68.1 g) from archaeological site 04-707. A stonewalled, rectangular enclosure with attached stone-filled terrace, the base of which has numerous branch coral offerings. The site is situated just inside (west) of the traditional land unit (*ahupua'a*) boundary and is interpreted as a Hale o Lono structure (Weisler and Kirch 1985:148, 150, Figure 12). The dedicatory coral was collected from the base of the stone-filled terrace on 19 June 2005 by MIW and submitted by MIW on 12 May 2008.

Comment: cal AD 1476–1697 (2 σ), 100% probability; cal AD 1536–1657 (1 σ), 100% probability.

$\delta^{13}C$ = –3.2‰
OZK959 Keawakalani 1351 ± 53 BP
Pocillopora sp. branch coral (6.8 g) from archaeological site B5-60 (01-60). A stone platform situated near the cliff edge, it is interpreted as a fishing shrine (Summers 1971:55). The dedicatory coral was collected from the northwest corner of the structure on 26 January 2007 by MIW and submitted by MIW on 12 May 2008.

Comment: cal AD 994–1241 (2 σ), 100% probability; cal AD 1044–1171 (1 σ), 100% probability.