

First Direct ^{14}C Ages on Hawaiian Petroglyphs



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KAHO'OLAWA HAS BEEN officially designated by the State of Hawai'i as a place for the practice of traditional and contemporary Hawaiian culture, including religion. As part of the process of returning the island to the state of Hawai'i, the Kaho'olawe Island Conveyance Commission authorized a project to document the rock art of the island and to determine the ages of selected petroglyphs. We present in this paper, as part of that project, the first direct radiocarbon ages for Hawaiian petroglyphs.

Our age-determination efforts rest within the context of a larger theory of Hawaiian rock art, culture, and prehistory. The Kaho'olawe petroglyph-dating project followed years of research on Hawaiian engravings (Cleghorn 1980; Cox and Stasack 1970; Lee 1988, 1989; Stasack and Lee 1993) and the archaeology of Kaho'olawe (Barrera 1984; Kirch 1985; Reeve 1992; Rosendahl 1987). However, it is beyond the scope of this paper to fully explore the broader cultural and archaeological implications of the dating work.

STUDY SITES AND SAMPLES

Kaho'olawe is the smallest of the eight major Hawaiian islands. Its position in the rain shadow of Haleakalā Volcano on Maui makes it Hawai'i's driest major island. From the perspective of petroglyph dating, aridity aids in the development and preservation of rock coatings that form over the engravings. Kaho'olawe's petroglyphs are found at 82 loci of 20 identified sites (Stasack and Lee 1993). Samples were collected from sites with the largest concentrations of petroglyphs: Hakioawa, Ahupu and vicinity, Kaukaukapapa, and Loa'a (Figs. 1, 2). These samples were assigned numbers in order of collection (K1, K2, K3, . . .). Where multiple samples were collected from a single motif or superimposed motifs, letters were

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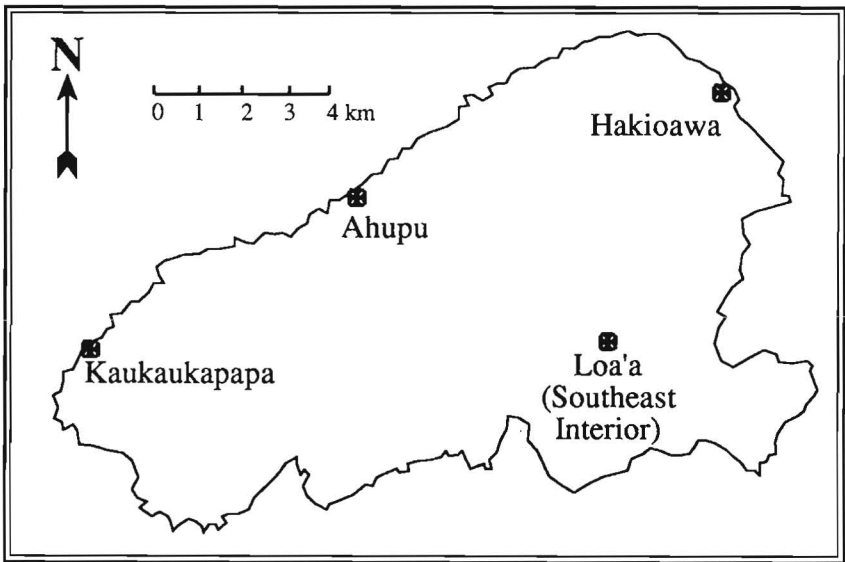


Fig. 1. Petroglyph sites on Kaho'olawe. Petroglyphs were dated from Hakiowa, Ahupū and vicinity, Kaukukapapa, and Loa'a (indicated on map as Southeast Interior).

assigned. For example, a stick figure (K16B) is superimposed over a triangular-bodied figure (K16A).

Loa'a, the southeast interior upland site, has experienced erosion of most of the solum. The soil that is left is a B-horizon "hardpan" of sesquioxides and the underlying regolith. Most of the petroglyphs are found engraved on a lag of regolith boulders. Loa'a has the lowest ratio of triangular-bodied figures to stick figures, so at this site we focused on dating stick figures on boulders in relatively undisturbed contexts. Some of the variation among the stick figures is shown in samples K10, K11, and K12 (Fig. 2).

The petroglyphs at the Ahupu site and vicinity are concentrated in a narrow bay with evidence of temporary and permanent habitation. Although volcanic-glass hydration dating is an experimental method in Hawai'i, the artifacts at this site yield glass-hydration ages that range from c. A.D. 1369 to 1443, suggesting early cultural use of the bay (Reeve 1992). Petroglyphs include human figures and zoomorphs, notably goats. Goats were introduced in the early historic period, perhaps in A.D. 1793 (Vancouver 1798). Samples were dated from petroglyph K16B (stick figure), which was superimposed over K16A (triangular-bodied figure). Petroglyph K15B is a goat that was superimposed over K15A (a stick figure); the stick-figure sample was radiocarbon dated. A triangular-bodied figure with a bird head (K19) was also selected for dating.

Hakiowa contains the largest concentrations of archaeological sites on Kaho'olawe, including house terraces and platforms, *heiau*, middens, burials, and petroglyphs (Kirch 1985). Stratigraphic age control indicates that the locality was occupied for more than 300 years, from c. A.D. 1280 to 1610 (Reeve 1992). In addition to stick figures (K23, K26), we sampled a pecked fish-hook motif (K22)—the only one rediscovered on the island.

Kaukukapapa contains a cluster of small occupation sites, a fishing shrine, and

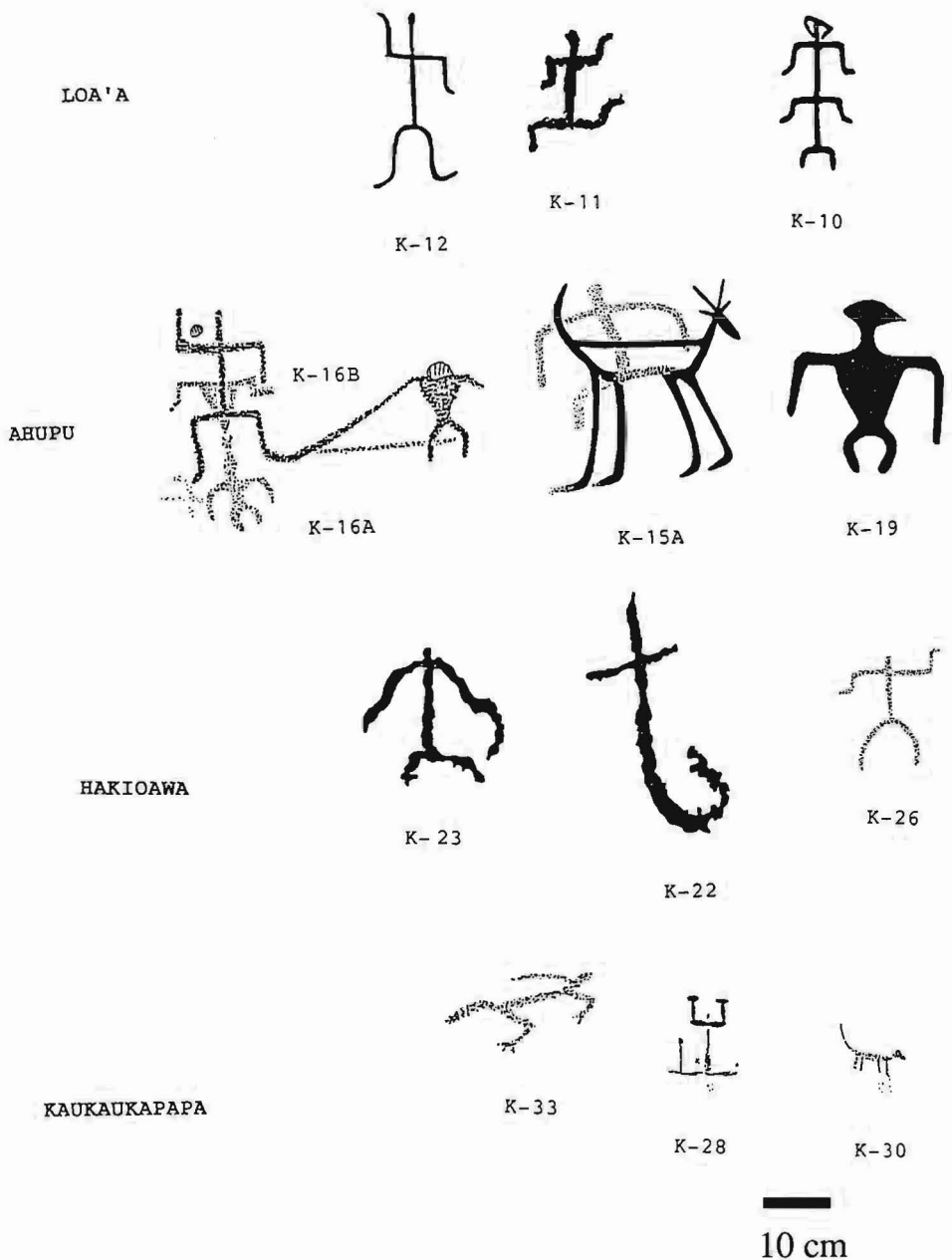
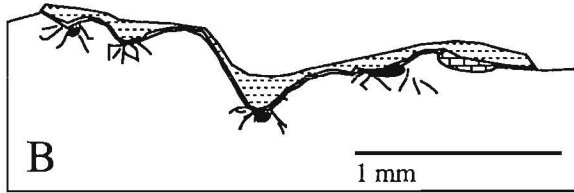
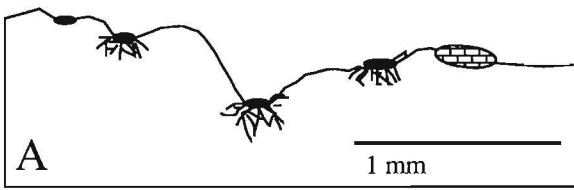


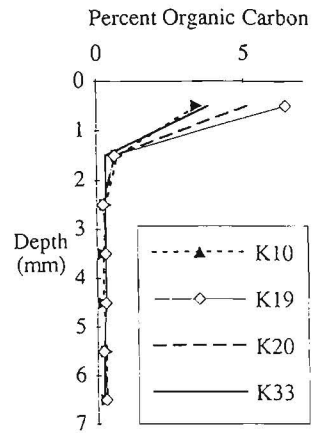
Fig. 2. Petroglyphs radiocarbon dated in this project.

the largest concentration of petroglyphs on Kaho'olawe. An upside-down stick figure (K28), a stick figure lying down (K33), and a dog (K30) were sampled.

Of the petroglyphs sampled but not radiocarbon dated, we also examined another five (K15B, K20A, K20B, K20C, K31) by electron microscopy to assess the relative development of rock coatings formed on top of different engravings. In the cases of K15A and K15B, and K20A, K20B, and K20C, there was a visual



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Figs. 3–4. Fig. 3. Idealized sequence of events whereby ^{14}C -dated organic matter is trapped underneath rock coatings: A. Organic matter is added to the petroglyph in the form of charcoal rubbed on a petroglyph, lichen with thalli that penetrate into rock, and fungi that weather rock and leave remains. B. Silica glaze encapsulates organic matter on surface and in weathering rind, and the entombed organic matter stops exchanging carbon dioxide with the atmosphere. Fig. 4. Depth profiles of abundance of organic carbon in subaerial weathering rinds on natural basalt boulders immediately adjacent to petroglyphs K10, K19, K20, and K33. The organic carbon is what is left after pretreatment and is measured by combustion; methods are elaborated in the text.

difference in the rock coatings, and we wanted to find the cause for this. The coating on the superimposed goat (K15B) looked much lighter than that on the stick figure K15A. Engraving K20 had three components with different degrees of coating development, possibly suggesting that the motif was retouched at different times. In the case of K31, the issue was whether any rock coating had formed on a fresh-looking, triangular-bodied figure.

METHODS

We assume the following sequence of events in order to constrain the age of Hawaiian rock engravings with radiocarbon measurements (Fig. 3):

First, a boulder is engraved. This process removes the preexisting rock coating and weathering rind.

Second, epilithic organisms (lichens, fungi, algae, cyanobacteria) grow in the engraving, colonizing rock surfaces (Jackson 1971). These organisms weather the rock and create pores (Jackson and Keller 1970), some of which in turn are filled with organic material (Cochran and Berner 1993). Alternatively, humans may add charcoal to the engraving.

Third, inorganic rock coatings of silica glaze (Curtiss et al. 1985; Dorn 1995; Dorn and Meek 1995; Farr and Adams 1984) and rock varnish (Dorn et al. 1992b) begin to encapsulate rock surfaces, typically starting in surface depressions.

Fourth, these coatings entomb organic matter that is present on the surface and in pores in the weathering rinds.

If this conceptual model is accurate, ^{14}C measurements on organics entombed by rock coatings provide minimum ages for the rock art. This is analogous to radiocarbon dating organics in a buried soil that has formed over an archaeological feature—only on a different scale. There are three general steps in the radiocarbon age determination of Kaho‘olawe petroglyphs, which involve testing the assumptions in this conceptual model.

Step 1

The first step is to test the assumption that the petroglyph-making process “resets” the clock by engraving below the layer of organic matter in the old weathering rind. The aim is to find out how much organic matter could potentially have been “inherited” from a time before the engraving was made. Different rock types, and the same rock type in different environmental settings, may have different profiles of organic matter concentration with depth in a weathering rind (Dorn 1994a; Nobbs and Dorn 1993).

Depth profiles were sampled by digging out centimeter-scale pieces from “natural” surfaces adjacent to petroglyphs. One depth profile was completed for each site: next to K10 at Loa‘a; next to K19 at Ahupūiki; next to K26 at Kahioawa; and next to K33 at Kaukauptapa. Samples were collected from approximate depths of 0–1 mm, 1–2 mm, 2–3 mm, 3–4 mm, 4–5 mm, 5–6 mm, and 6–7 mm. Samples were chemically pretreated in the same fashion as the petroglyph samples, with HCl, NaOH, and HF. Then the residue was burned and the amount of organic carbon compared to the dry weight of the sample (Dean 1974).

Step 2

The second step is to test the assumption that organics were deposited on engraved surfaces, or in the weathering rind, and then covered by rock coatings. Petroglyphs were sampled in a way that minimized damage while maximizing the possibility for obtaining reliable radiocarbon ages. Pieces of basalt ~1–2 mm in diameter were chipped from each petroglyph with a tungsten-carbide needle. These were pried from surface depressions where epilithic and endolithic organisms would tend to be coated first with silica glaze.

Rock chips were then placed in epoxy and cross sections polished for examination under a scanning electron microscope (SEM), in this case a JEOL JXZ-8600 electron microprobe. The sections were imaged with secondary electrons (SE), which provides topographic information (Krinsley and Doornkamp 1973), and backscatter electron microscopy (BSE). Images formed by backscattered electrons reveal variations in sample composition, since the backscattered-electron yield is a function of the average atomic number (Z) of the sample. The various shades of gray in the image represent varying elemental compositions within the sample, with lower Z regions appearing darker and higher Z regions appearing brighter (Krinsley and Manley 1989). The combination of SE and BSE allows the investigator to quickly identify the location of organic matter (Watts 1985), which has a

low atomic number (appears dark in BSE) but possesses a topographic presence and charges (appears bright in SE). The presence of organic matter is then confirmed with wavelength dispersive spectrometry (WDS).

Step 3

SEM examination is also used to assess whether rock coatings are deposited in a series of stratigraphic layers on top of the organics. This is analogous to excavating an archaeological site, finding charcoal, and deciding whether it should be dated. If charcoal is found in a layered stratigraphy, its temporal relationship to surrounding archaeological material may be established. This type of microstratigraphic analysis was originally developed for rock-varnish dating (Dorn et al. 1986), but it is now standard in rock-art dating (Chaffee et al. 1993; Watchman 1993).

Good stratigraphy in silica glaze is important in dating Kaho'olawe petroglyphs, because the objective is to get as close a minimum age as possible. If the rock coating eroded and then re-formed, the encapsulated organics might post-date the engraving by a considerable amount of time, as others have found when rock coatings are not well layered (Dorn 1994a, 1994b; Nobbs and Dorn 1993).

Chemical Pretreatment and AMS ¹⁴C Measurement

For samples with an intact stratigraphy, the rock coating was removed with a tungsten-carbide needle in the laboratory under 45x magnification. The remaining material was then powdered and pretreated to remove younger organic molecules that might move with capillary waters (Burchill et al. 1981; Gillespie 1991; Heron et al. 1991; Osterberg et al. 1993; Warren and Zimmerman 1994). Pretreatment has proven to be a vital part of obtaining reliable radiocarbon ages (Taylor 1987). The pretreatment used for our Kaho'olawe samples consisted of HCl, NaOH, and HF. Although an unusual choice, HF has been found necessary to remove younger organics that can adsorb to clay minerals in rock varnish (Dorn et al. 1989). The insoluble residues were then sent to the New Zealand accelerator for the making of the target (i.e., carbon dioxide gas from the organic material) and for the accelerator mass spectrometry (AMS) ¹⁴C measurement. These radiocarbon measurements were then calibrated (Stuiver and Reimer 1993).

Relative Coating Development

We also examined the relative development of rock coatings formed on top of petroglyphs. Using WDS and energy dispersive detectors, we studied the chemistry of the rock coatings. Analyses with the JEOL microprobe were made with a 10 μm spot size at the base of the rock coating from the dated petroglyphs, at the contact with the organic matter. Using BSE, we also examined the thickness and layering of the rock coatings. Examination of layers may permit relative dating, and with enough future data, it may also permit individuals to study sequential palaeo-environmental fluctuations at engraving sites (Dorn 1992).

RESULTS

The first assumption—that the engravings were carved beneath organics stored in the preexisting weathering rind—appears to be true for profiles from each of the sites. Figure 4 reveals that the concentration of organic matter drops off rapidly at depths greater than about a millimeter. At a depth of $\sim 2\text{--}3$ mm, concentrations drop to less than 0.003 g/g (grams of organic carbon per gram of pretreated rock material). The Kaho'olawe depth profiles drop off more rapidly than those from the vesicular lava flows of Hualalai Volcano (Dorn 1994a:20), probably because organic matter can move more readily through already established vesicle pores. In contrast, the more massive basalts engraved on Kaho'olawe need to be weathered before organic matter can be deposited.

In those samples submitted for ^{14}C AMS measurement, organics were encapsulated by layered rock coatings, meeting the second and third assumptions in the conceptual model (Fig. 3). The organics were encapsulated by silica glaze (Figs. 5–8). Sometimes, charcoal was found beneath the rock coating (Fig. 5); in other cases, the material dated was unidentified organic matter (Fig. 6). However, the second and third assumptions were not valid for all the samples that we collected on Kaho'olawe Island. Some petroglyphs did not display an intact stratigraphy, while others lacked enough organic matter to date. These petroglyphs were not considered further for AMS ^{14}C dating.

Table 1 presents ^{14}C ages for subcoating organics, collected from 13 separate petroglyphs. The measurements are presented in chronological order. Due to variability in the production of radiocarbon (Stuiver and Reimer 1993; Taylor 1987), it is possible for a single radiocarbon date to have several different calibrated calendar ages. This is shown by multiple ages within the parentheses in the last column (calibrated age). The best way to view these radiocarbon ages is in terms of an age range, as given in Table 1. For example, organics encapsulated on the fish-hook petroglyph (K22) have an age range of A.D. 1230–1290 (1 sigma error).

Our qualitative evaluation of the development of rock coatings revealed apparent differences at the electron microscope level that could correspond to visual differences seen in the field. The silica-glaze coating on the goat motif (K15B; Fig. 7), which was superimposed across an earlier stick figure (K15A), looked much lighter than the coating on K15A—perhaps because K15A had a thicker coating (Fig. 6).

Engraving K20 had three components with different degrees of coating development (Fig. 8), consistent with the hypothesis that the motif was retouched at different times. The thick lower layer of iron-rich silica glaze indicates that K20C is older than K20B, and the lack of a lower layer of iron-rich silica glaze indicates that K20A is the youngest of the three sections. An alternative explanation is that the motif was made all at once, and that very different rates of silica-glaze accretion can occur side by side.

In the case of K31, the petroglyph had no observable development of any rock coating. This contrasts with a sample from the adjacent rock surface, which had a silica glaze more than 0.1 mm thick. It is unlikely that the particular microenvironment on this panel is different from others at Kaukaupapa. Rock coatings of silica glaze are ubiquitous on natural rock surfaces and most petroglyphs here.

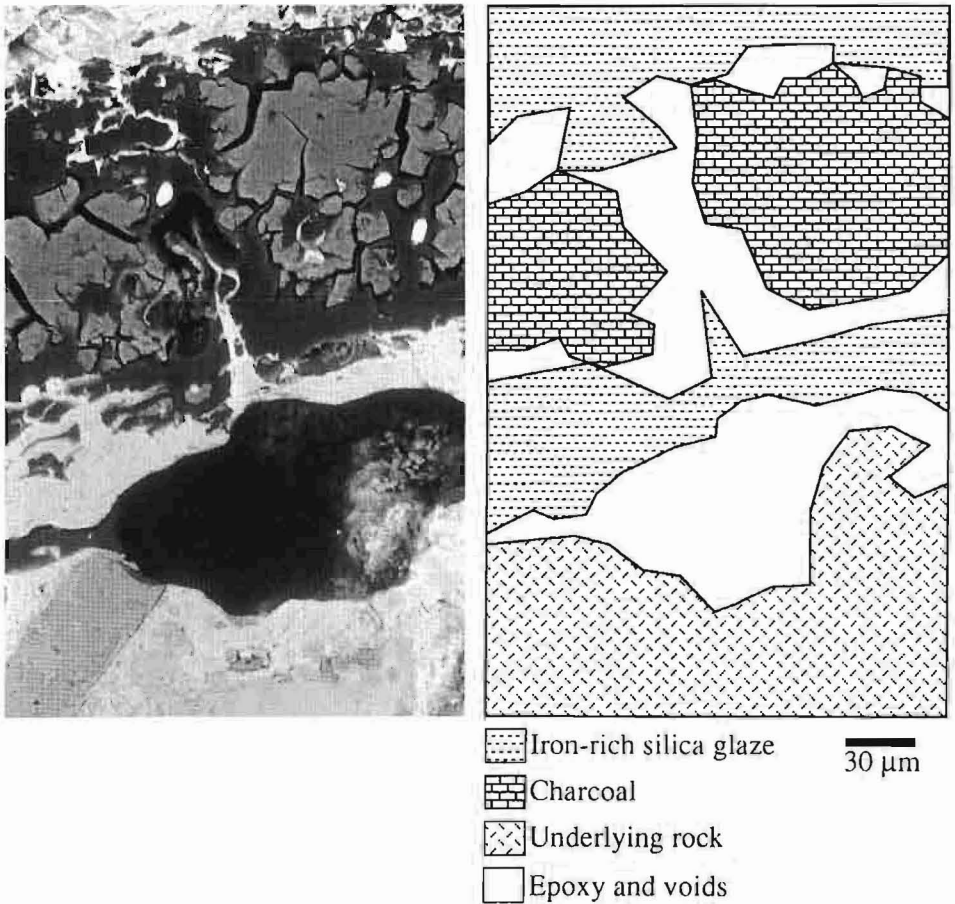
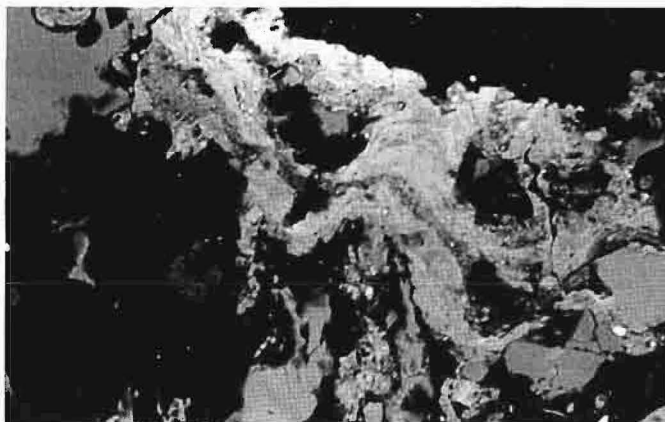


Fig. 5. Microstratigraphic context of organic matter sampled from petroglyph K22. The image on the left was taken with backscatter electron microscopy; the map on the right corresponds to the image. The charcoal, because it is composed of lighter elements (C, N) is darker than either the underlying rock or the adjacent iron-rich silica glaze. The silica glaze has encapsulated charcoal, which was applied to the petroglyph groove after the motif had been manufactured.

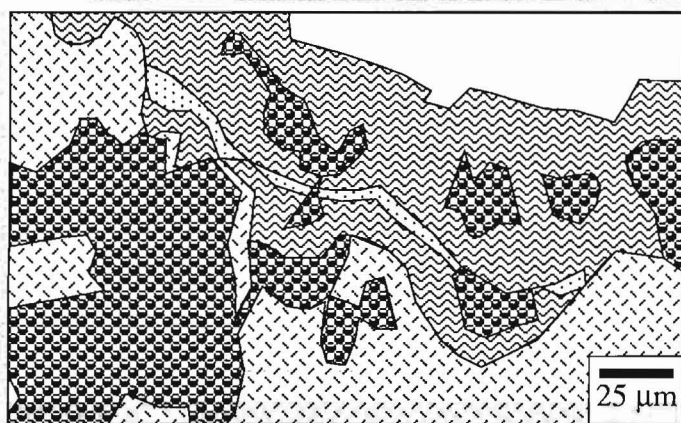
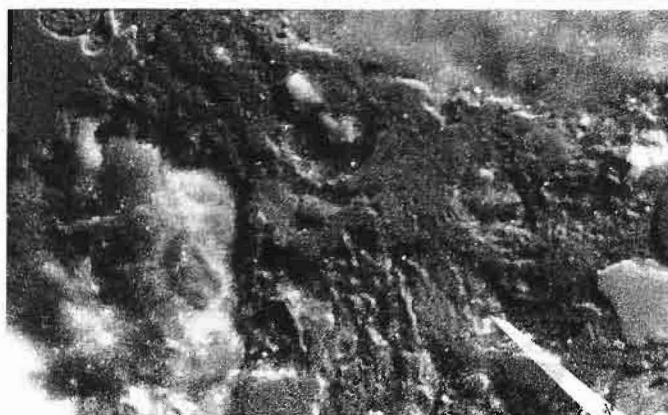
The lack of a rock coating on petroglyph K31, therefore, suggests that K31 is very young. Because the youngest petroglyphs (K10 and K19) in our sample had rock coatings tens of microns thick—admittedly, at a different site—we suspect that K31 was made during the historic period.

Fig. 6 (*facing page*). Microstratigraphic context of organic matter sampled from petroglyph K15A. The top image was taken with backscatter electron microscopy; the middle one, with secondary electron microscopy, showing topography. The location of the organic matter can be determined by matching places where the image is dark in backscatter, but present in secondary. This was confirmed (bottom map) by examining the material with wavelength dispersive spectrometry; a strong carbon signal appeared in the areas mapped as "subcoating organics in weathering rind." The sequence is interpreted as follows: First, the petroglyph was grooved. Then, organisms colonized the rock surface depression because water collected there. As organisms grew on rocks, they left remains in the weathering rind. When the rock coating began to develop, these subsurface organics were entombed in the weathering rind. A radiocarbon date on these weathering-rind organics, therefore, provides a minimum age for the manufacture of the petroglyph.

Backscatter Electron Image of Average Atomic Number



Secondary Electron Image of Topography







-  Rock varnish (Fe-rich/Mn-poor)
-  Aluminum-rich silica glaze
-  Organics
-  Underlying rock

Table 1. MINIMUM AGES FOR KAHO'OLAWE ISLAND PETROGLYPHS

PETROGLYPH SAMPLED (SEE FIG. 2)	NZA	AMS	CALIBRATED AGE WITH 1 SIGMA RANGE
	LAB NO.	¹⁴ C AGE	
K10: triangle head, generation figure	3613	175 ± 61	A.D. 1660–1950
K19: triangle body with bird head	3610	216 ± 63	A.D. 1650 (1670, 1790) 1950
K26: stick figure; right arm raised	3752	357 ± 59	A.D. 1460 (1510, 1600, 1620) 1640
K16B: stick figure ^a	4047	408 ± 87	A.D. 1432 (1465) 1634
K15A: stick figure (under goat)	3612	541 ± 64	A.D. 1320 (1410) 1440
K16A: triangular body ^a	4051	578 ± 89	A.D. 1301 (1401) 1434
K30: dog	4053	630 ± 100	A.D. 1286 (1310, 1353, 1385) 1416
K11: running stick figure	3746	652 ± 63	A.D. 1290 (1300, 1370) 1400
K12: stick figure; left arm raised	4048	657 ± 91	A.D. 1282 (1303) 1404
K22: fish hook	3611	765 ± 61	A.D. 1230 (1280) 1290
K28: upside-down stick figure	4050	873 ± 86	A.D. 1037 (1188) 1272
K33: lying-down stick figure	4052	978 ± 88	A.D. 992 (1029) 1168
K23: stick figure	4049	985 ± 96	A.D. 983 (1027) 1168

^aK16B is superimposed over K16A.

DISCUSSION

In discussing this first foray into the radiocarbon dating of Hawaiian petroglyphs, we have three general comments. First, the ages are archaeologically reasonable. Second, the ¹⁴C measurements in Table 1 are best interpreted as minimum age constraints. Third, silica glaze in Hawai'i appears to be a wonderful chronometric tool, but more research is required to move silica-glaze-encapsulated ¹⁴C ages beyond the status of an experimental technique. These topics will be considered in order.

Preliminary Interpretation of Ages

The ¹⁴C ages are best interpreted as minimums for the timing of petroglyph manufacturing. This is because the AMS measurements are made on organic carbon that was added to the engravings after they were created. The lag time between petroglyph manufacturing and the encapsulation of the dated organics is discussed below.

There is an apparent offset between the occupation of Kaho'olawe—documented by younger radiocarbon ages associated with excavations—and the older petroglyph ages. One possible explanation could be that Hawaiians were visiting the island and producing rock art before the time when most settlements were occupied. Another possibility is that petroglyph making may have been one of the first creative activities that took place upon the discovery and/or occupation of a site. By their nature petroglyphs are exposed and easier to find than buried occupation sites. The apparent older ages for the petroglyphs in settlement areas may support the possibility that at the time of settlement, petroglyph making was part of the ceremonial claiming or proclamation of a site. There is a third, methodological explanation: the sample size is limited for both petroglyphs and excavated sites. We do not think it likely that we happened to select the earliest petroglyphs. Similarly, the earliest occupation sites may remain unexcavated.

Backscatter Electron Image

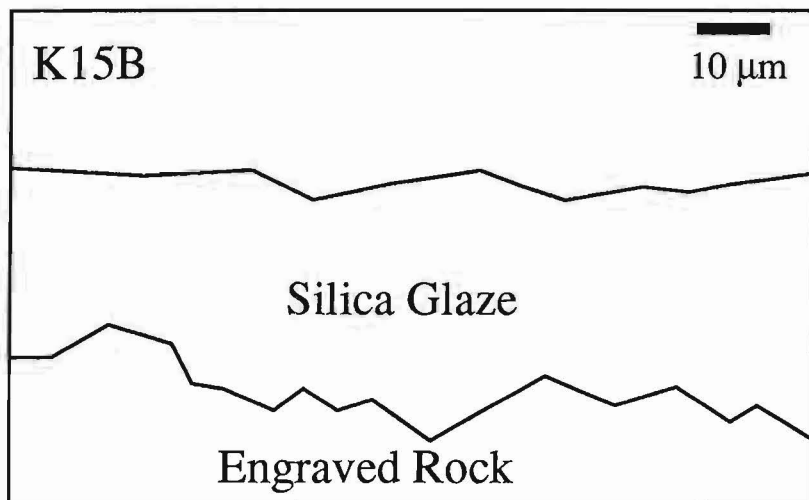
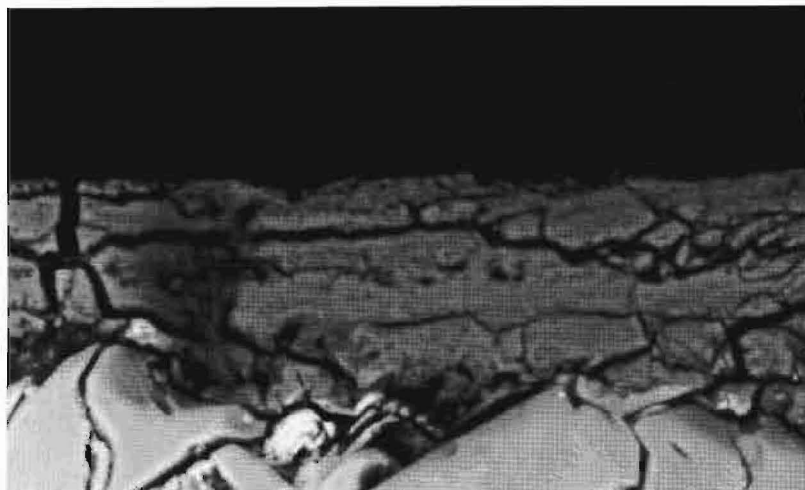


Fig. 7. Microstratigraphic observation of petroglyph K15B, a goat that was superimposed on a stick figure (K15A). This backscatter electron micrograph (top) shows the typical development of a thin silica glaze formed on top of the underlying olivine, as depicted in the corresponding map (bottom). The microstratigraphy of the silica glaze on petroglyph K15A is much thicker and has a more complex stratigraphy. Therefore, the goat image is probably considerably younger than the stick figure.

Three periods of petroglyph activity on Kaho'olawe can be tentatively identified. Further age control will help to refine this preliminary assessment.

In the early period, before c. A.D. 1400 or 1500, stick figures were the chosen form for anthropomorphs, and motifs were made using both straight and curved lines. On Kaho'olawe, as on all the Hawaiian Islands, stick figures were much alike. For the most part, the differences were in proportion, size of line, and technical skills. Most were pecked, but some were pecked and then abraded. We

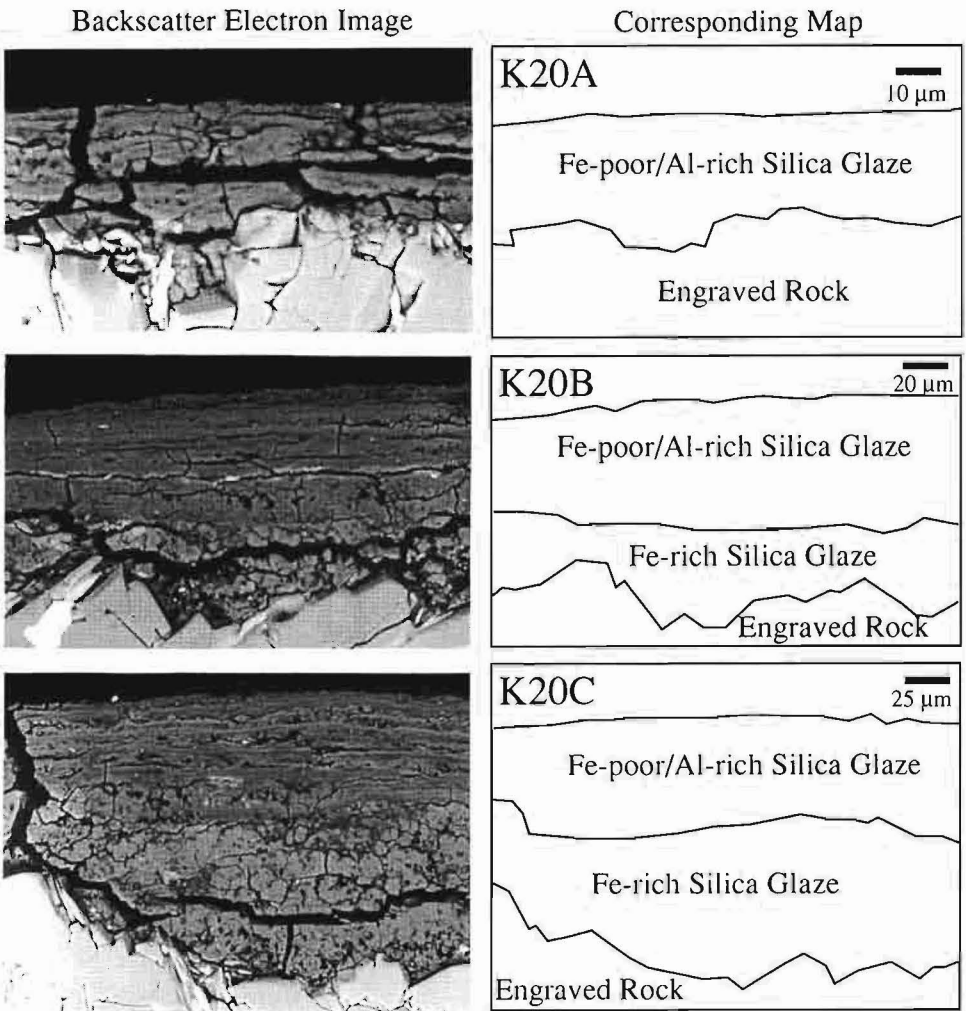


Fig. 8. Microstratigraphic observations of petroglyph K20, with subsamples K20A, K20B, and K20C. All images were taken with backscatter electron microscopy. They are typical of the stratigraphy of the coating on each part of the petroglyph. *K20A*: The coating on K20A is much thinner, and in places it has not yet formed on the underlying rock. This image shows a typical pecking mark where the coating is less developed. Its layered structure and its chemistry rich in aluminum indicate that it formed during the same period of time the upper layer of K20A and K20B formed. *K20B*: A lower layer rich in iron is still present, but it does not always occur and is much thinner where it does occur. This suggests that K20B was engraved at the end of the period when the iron-rich silica glaze was forming; the glaze was deposited in the deeper depressions first. The environment then changed to conditions where the type of coating formed was richer in aluminum. *K20C*: The silica-glaze coating is evenly divided between the lower, more iron-rich layer and the upper, more iron-poor (aluminum-rich) layer. The lower iron-rich layer has a more massive appearance, while the aluminum-rich coating has a more layered appearance. The change to more aluminum could be a reflection of more clay minerals.

present nine AMS ^{14}C minimum ages from this early period. At Loa'a, 85 percent of the anthropomorphs are stick figures, suggesting that this site was used more in relatively ancient times. In addition, Loa'a displays 33 of the island's 34 *luaiki* (cupules).

Our minimum ages support the hypothesis that the most ancient petroglyphs were linear and that for some reason, around A.D. 1400–1500, some petroglyph makers began to use lines to enclose and define a shape. This extended the artist's range for visual representation of particularized forms and expressive content. For example, an inverted triangle was used both as an expression of strength and as a visual representation of the mass of the body of a broad-shouldered male.

In the middle period, A.D. 1400/1500–1800, triangular torsos appeared and overlapped with stick figures. We obtained four AMS ¹⁴C minimum ages for this period: the stick figure from Ahupū, A.D. 1432–1634; the stick figure from Hakioawa, A.D. 1460–1640; the triangular-bodied figure with a bird head from the gulch west of Ahupū, A.D. 1650–1950; and the composite figure with a bisected inverted triangular head, A.D. 1660–1950, from Loa'a. The emergence of the triangular body represents a move from the use of line to the use of shape, a step toward the representation of three-dimensional form. A line is, after all, a human-made convention most often used to suggest a contour, an edge, or a form that is essentially linear, such as the fish-hook petroglyph at Hakioawa (K22).

Probably well into the middle period, stylizations appeared, such as the bird-man and various body types with headdresses, winged arms, and unusual proportions. In this period on Kaho'olawe, as on other islands, it is likely that the first petroglyph representations of family gods, 'aumakua, were made in the form of humans with animal attributes, such as birds, turtles, dogs, and fish. Influences and/or connections from Lāna'i and Maui appear strong during the middle period. Compared to the petroglyphs on the other islands, Kaho'olawe's curved-triangular-bodied figures most resemble those from Maui and, in particular, the petroglyphs at Kukui Point, Lāna'i.

In the final period, after A.D. 1800, names and words were inscribed. Figures and animals in heterogeneous styles continued to be made, intermingled with older images and writings. The lettering may be attributable to the influence of nearby Lahaina, Maui, where a printing press and a school were established in the early nineteenth century. The name of a man, Keliikipi, living on Kaho'olawe during the 1866 census, is inscribed on a boulder at the bay east of Ahupū. We chose not to radiocarbon-date any petroglyphs that were obviously from this period (although this would be a good test of potential errors and should be done when funds become available). Approximate ages of such images as goats, various written names and words, and sailing ships are evident.

A conservative interpretation of our minimum ages is that petroglyphs were made at Kaho'olawe for at least 80 percent of the time that the Hawaiian Islands have been occupied, perhaps with fallow periods when no petroglyphs were made. The stick figure at Hakioawa, K23, located approximately 200 m uphill from K22, yields the oldest minimum age from Kaho'olawe. The figure has a very small head, wavy arms, and short legs. The leg on the left ends in an irregular shape suggesting three toes or possibly a club foot (Fig. 2). Hawaiian scholar Rubellite Kawena Johnson (pers. comm. 1994) thinks that this petroglyph might depict the constellation of *Maui ki'i ki'i a kalana*, known in other parts of the Pacific as *Mai tiki*, the god Maui. The foot is a key element in this representation and might tie in with K33, the unusual, nearly horizontal figure from Kaukaupapa at the opposite end of the island, which also has one three-toed foot (Fig. 2).

Petroglyph K33 may depict the Maui constellation as seen at another angle or position in the sky, or from another geographical location. We note that K23 (A.D. 983–1168) and K33 (A.D. 992–1168) have overlapping minimum ages, despite their location at opposite ends of Kaho‘olawe.

Subcoating Organics Provide Minimum Ages

Rock coatings and the weathering rind on boulders constitute the surface matrix into which petroglyphs are engraved. Organics in this preexisting weathering rind would likely be older than the engraving. Most petroglyphs were engraved to depths of about 2–4 mm, where concentrations of organic matter drop to less than 0.003 g/g (Fig. 4). The effect of this contamination would make ^{14}C ages ~ 20 –60 years older at concentrations of organics in the petroglyph samples (3–5 percent). This assumes a worst-case scenario, in which the organics in the “inherited” weathering rind had a “dead” radiocarbon age. In other words, organics inherited from a preexisting weathering rind probably have a minimal effect on the radiocarbon ages in Table 1, at most doubling the small uncertainty associated with the AMS measurement. Before we can assign a specific correction for each petroglyph age, however, we need to complete further work on depth profiles of organics in weathering rinds on Kaho‘olawe.

The only other source of contamination from older organics might be charcoal. As seen in Figure 5, some of the encapsulated organics are composed of charcoal. A reasonable interpretation is that the petroglyphs were marked with charcoal sometime after manufacturing. If the charcoal was derived from a woody species, the wood could predate the petroglyph. It then becomes pertinent to ask how long the prehistoric trees of Kaho‘olawe Island lived. We note, however, that this issue also applies to any ^{14}C age of charcoal at Kaho‘olawe sites.

Although older sources of carbon may exist as potential contaminants for many reasons, they are far less likely to have influenced the ages in Table 1 than factors that would force ^{14}C ages in a younger direction. First, there is a time lag between engraving and the application of charcoal or surface colonization by epilithic organisms. Second, there is a time lag in the establishment of rock coatings. Silica glaze, the most dominant rock coating on Kaho‘olawe petroglyphs, can begin to form within a few decades in drylands on Hawai‘i Island (Curtiss et al. 1985; Farr and Adams 1984). Third, we assessed the stratigraphy of the rock coatings from a few subsamples and assumed that this random sample accurately portrays the nature of rock coatings on the petroglyph. If some subsamples were not stratigraphically sealed, however, younger organics could become incorporated into the weathering rind. Fourth, we assume that the harsh chemical pretreatment leaches out postcoating organic molecules; this chemical pretreatment, however, has yet to be tested for organics encapsulated by silica glaze. Fifth, the amount of organic material dated is quite small, a few milligrams; although great care is taken in the laboratory to avoid contamination, modern organics are ubiquitous—for example, pollen in dust. These factors are not quantified, and we have gone to great effort to minimize potential contaminants. However, considered all together, these factors make it most likely that the radiocarbon ages in Table 1 provide minimum-limiting age ranges for the Kaho‘olawe petroglyphs.

Evaluating Silica Glaze as a Chronometric Tool

Silica glaze is the most common rock coating in the Hawaiian Islands (Dorn 1995; Dorn et al. 1992*b*; Farr and Adams 1984). This rock coating occurs in warm deserts (Fisk 1971; Hobbs 1917), in cold deserts (Weed and Ackert 1986), along tropical rivers (Alexandre and Lequarre 1978), in humid temperate settings (Robinson and Williams 1987), and in various archaeological contexts (Hamilton 1984). We are not the first to use silica glaze in the dating of rock art. Others have used organics entombed by silica glaze to place minimum ages on rock paintings (Watchman 1992, 1994) and petroglyphs (Nobbs and Dorn 1993).

Although silica glazes are characterized by amorphous silica, different elements can occur in substantial quantities; for example, Al_2O_3 can reach greater than 50 percent in some glazes from Maui, and Fe_2O_3 can reach greater than 10 percent in some glazes on desert pavement cobbles from Peru and the southwestern United States (unpublished electron microprobe data). Electron microprobe analyses of the silica glaze on Kaho'olawe show considerable variation in the composition of aluminum, iron, and trace elements (Table 2). However, the general chemical characteristic of silica glaze is a combination of abundant amorphous silica and a high concentration of aluminum.

Silica glazes probably form from soluble aluminum silicate complexes, which are ubiquitous at the water-rock interface (Browne and Driscoll 1992). Incipient silica glazes can be disturbed by violent wetting (Curtiss et al. 1985). In contrast, if the wetting is "gentle" (e.g., dew or short-duration, low-intensity rain), a bond forms between the rock and soluble Al-Si complexes, which then precipitate as an incipient glaze formation. Once the coating is well established, silicic acid and soluble Al-Si complexes bond to the silica glaze more easily, because "silicon need have no residence time in solution as silicic acid before it is incorporated into a solid reaction product at the surface of a mineral" (Casey et al. 1993:255). This model of silica glaze is discussed in detail elsewhere (Dorn and Meek 1995).

Previous work has established that silica glaze (Dorn et al. 1991; Farr and Adams 1984; Friedmann and Weed 1987; Weed and Norton 1991) and rock varnish (Dorn et al. 1992*a*, 1992*b*; Francis et al. 1993), as well as other rock coatings (Brown and Martin 1993; Russ et al. 1994), can encapsulate epilithic and endolithic organic matter. However, in the experience of the second author in examining rock coatings, Hawaiian silica glaze provides the "tightest" encapsulation of any rock coating. There are relatively few capillary pores in Hawaiian silica glaze, compared to other rock coatings (Dorn and Krinsley 1991; Dorn and Meek 1995), and the organic matter subjectively appears fresher than organics encapsulated by other accretions. The ability of silica glaze to form rapidly (Dorn and Meek 1995)—for example, on Hawaiian lava flows (Curtiss et al. 1985)—may explain why it makes such a good encapsulating agent for dating organics on Kaho'olawe petroglyphs (Figs. 5, 6).

The rapid formation of silica glaze in Hawai'i makes it potentially useful as a field chronometric tool to assess whether petroglyphs are late prehistoric to early historic. As an example, the complete lack of silica glaze on K31 contrasts with the presence of tens of microns of silica glaze on the youngest radiocarbon-dated petroglyphs (K10, K19). The historic goat petroglyph (K15B) also had a coating of silica glaze (Fig. 7).

Table 2. MICROPROBE PROFILES OF SILICA GLAZE ON KAHO'OLAWE PETROGLYPHS

PETROGLYPH	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	SO ₃	K ₂ O	CaO	TiO ₂	MnO	Fe ₂ O ₃	BAO	TOTAL
K10	0.55	0.10	16.19	72.44	0.02	0.27	2.24	0.18	0.06	0.00	4.14	0.09	96.28
K19	0.19	0.17	10.12	67.41	1.88	0.20	1.07	0.40	0.20	0.48	16.97	0.03	99.12
K26	0.34	0.50	14.11	73.55	0.87	0.25	0.61	0.78	0.97	0.20	3.16	0.10	95.44
K16B	0.29	0.96	13.13	80.31	1.19	0.17	0.22	0.54	0.98	0.14	1.75	0.03	99.71
K15A	0.09	0.88	15.49	58.04	1.05	0.15	0.50	0.38	0.17	0.08	18.80	0.06	95.69
K16A	0.15	0.60	21.54	62.07	1.42	0.23	0.61	0.47	0.22	0.15	7.54	0.00	95.00
K30	0.09	0.80	14.23	75.59	1.19	0.25	0.47	0.70	0.17	0.07	5.56	0.02	99.14
K11	0.40	0.81	13.40	74.07	0.66	0.29	0.50	1.04	0.25	0.07	2.23	0.00	93.72
K12	0.67	0.90	24.16	65.17	0.48	0.17	0.84	0.66	0.70	0.22	4.32	0.01	98.30
K22	0.60	1.44	30.17	49.84	1.08	0.25	1.55	1.11	0.07	0.41	10.11	0.09	96.72
K28	0.14	1.67	19.00	66.90	1.55	0.25	1.70	0.20	0.15	0.11	7.04	0.12	98.83
K33	0.55	0.80	18.11	71.60	1.37	0.29	0.90	0.33	0.20	0.09	4.29	0.14	98.67
K23	1.04	0.44	22.70	66.48	1.07	0.20	0.55	0.37	0.19	0.09	3.30	0.19	96.62

The next step in the development of this potential field tool would be “calibrating” how long it takes silica glaze to begin to form in different microenvironmental settings on surfaces with a known age (e.g., lava flows, tombstones). For example, we note the presence of silica glaze from the top to the bottom of the 1969–1973 Mauna Ulu flow on Hawai‘i. This type of information could also be important in assessing the lag time between petroglyph engraving and silica-glaze encapsulation—information that could be used to estimate a correction factor for the radiocarbon ages in Table 1.

Silica glaze shows great promise as a tool to help extract chronological information from Hawaiian petroglyphs, as well as from rock art in other settings (Nobbs and Dorn 1993; Watchman 1992, 1994). However, before radiocarbon ages on organic matter encapsulated by this rock coating can be fully accepted, two additional tests are required. These tests are best conducted in Hawai‘i.

First, the silica-glaze system has not been subjected to independent tests of accuracy. For example, rock varnishes were tested as an encapsulating agent on the surfaces of Hualālai lava flows, when subvarnish organic ^{14}C ages were compared with conventional ^{14}C ages on subflow charcoal (Dorn et al. 1992*b*). The detailed geological mapping available for Hualālai (Moore and Clague 1991; Moore et al. 1987), in combination with the ubiquitous nature of silica glaze on these lava flows, would make Hualālai an ideal site to test the accuracy of silica-glaze-encapsulated ^{14}C ages.

Second, tests of the best chemical pretreatment of samples have not been conducted. We and Nobbs and Dorn (1993) are the only researchers to have chemically pretreated subglaze organics. Our pretreatment procedure is admittedly harsh, because we assume that treatment with HCl is necessary to remove carbonates by hydrolysis, treatment with NaOH is needed to remove mobile tiny humic acids (Osterberg et al. 1993), and treatment with HF is necessary to remove clays that can adsorb organics that move with capillary water (Gillespie 1991; Heron et al. 1991; Warren and Zimmerman 1994). This pretreatment was used because samples of subvarnish organics that were not pretreated as described yielded ^{14}C ages far younger than independent controls (Dorn et al. 1989). Independent testing of pretreatment procedures at sites with independent age control, such as Hualālai Volcano, are needed to assess the accuracy of ^{14}C ages on sub-silica-glaze organics. Until these tests are conducted, we recommend that lasers not be used to extract organic matter under silica glazes (Watchman and Lessard 1992), because pretreatment is not used and HF-treated cross sections have not shown integrity when they have been placed in a vacuum chamber for laser ablation (Nobbs and Dorn 1993).

CONCLUSIONS

We have presented 13 new AMS radiocarbon ages from organic matter that has been encapsulated by silica-glaze rock coatings on Kaho‘olawe Island petroglyphs. The only other age control on prehistoric Hawaiian rock art comes from Hilina Pali Petroglyph Cave on Hawai‘i: a single ^{14}C measurement calibrated to A.D. 1540–1720 on charcoal in sediment resting over a triangular-bodied figure (Cleghorn 1980). The minimum ages for Kaho‘olawe petroglyphs range from

A.D. 983 to 1168 for a stick figure to late prehistoric/early historic period for two triangular-bodied figures.

Although available evidence indicates that our ^{14}C ages are reliably interpreted as a minimum limit—that is, the petroglyph is older than the age range—two additional tests on the systematics of the method are required to move the technique beyond the experimental stage. The rock coating called silica glaze has not been subjected to independent tests to assess its reliability as an encapsulating agent. In addition, the best type of chemical pretreatment has not yet been determined. Both tests could be conducted in Hawai'i using available ^{14}C age control for lava flows of Hualālai Volcano (Moore and Clague 1991; Moore et al. 1987), and such tests would be of the utmost applicability for dating petroglyphs in Hawai'i and other tropical islands.

The age determination of rock art is currently being revolutionized, in part because of the ability to radiocarbon-date small amounts of carbon with accelerator mass spectrometry. Experimental efforts to date carbon in rock paintings (e.g., Chaffee et al. 1993; Clottes 1993; Loy 1993; Watchman 1993) and associated with petroglyphs (e.g., Francis et al. 1993; Nobbs and Dorn 1993) have yielded numerical ages where none had been available before. In this paper, we have continued the process of gathering new data on organic matter in a rock-surface context that had not been investigated previously: petroglyphs on dry tropical islands. While we believe that all evidence points to these ^{14}C ages being reliable minimum ages, we have attempted to place our measurements within the context of the entire effort of dating rock art, which is an iterative and experimental endeavor.

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ABSTRACT

We collected organics encapsulated by coatings of amorphous silica from 13 petroglyphs on Kaho'olawe Island, Hawai'i. Silica-glaze coatings can form within a few decades in Hawai'i. After backscatter electron microscopy of the overlying silica coating determined that it had been deposited in layers sequentially, organics were

treated with NaOH, HCl, and HF, and were radiocarbon-dated at the New Zealand accelerator. The minimum ages obtained for these Kaho'olawe petroglyphs indicate that they span at least 80 percent of the time that the Hawaiian Islands have been occupied. Stick figures are the oldest petroglyphs, but they overlap with other linear motifs (fish hook, dog) as well as the triangular-bodied figures, which came later. KEYWORDS: Petroglyph, Hawaiian Islands, Radiocarbon Dating.