Journal of Archaeological Science: Reports 2 (2015) xxx–xxx

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: http://ees.elsevier.com/jasrep

Alternative models of volcanic glass quarrying and exchange in Hawai'i

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ARTICLE INFO

Article history:
Received 18 October 2014
Received in revised form 21 February 2015
Accepted 15 March 2015
Available online 28 March 2015

Keywords:
Exchange
Common pooled resource
Volcanic glass
EDXRF
Hawai'i
Social complexity

ABSTRACT

138 volcanic glass artifacts recovered from Site 50–10–19–30173 at Ka'ūpūlehu, Hawai'i Island were sourced to Pu'uwa'awa'a using EDXRF. Site 50–10–19–30173 is a beach sand deposit with volcanic glass and other traditional Hawaiian artifacts that was sealed by an AD 1800–1801 lava flow. The proportion of Pu'uwa'awa'a volcanic glass in the assemblage is consistent with a cost surface model proposed recently. It is shown that the fall off in Pu'uwa'awa'a volcanic glass is exponential for the cost surface for Hawai'i Island, as it is for two alternative distance decay models, which also yield good fits to the volcanic glass data. A straight line distance overland model provides an easy way to generate predictions. A depot model, where Pu'uwa'awa'a volcanic glass is brought to Kahuwai Bay at Ka'ūpūlehu and distributed by canoe, fits the existing data somewhat better than the two overland transport models. It has been argued on the basis of distributional data and technological analyses that Pu'uwa'awa'a volcanic glass was a common pooled resource. The analysis presented here supports this idea by noting the lack of evidence for directional trade in the residuals of the fit to the exponential curve. Recommendations for future research are offered.

1. Introduction

At the time of Western contact in AD 1778, traditional Hawaiian society was among the most highly stratified and complex in Polynesia (Sahlins, 1958; Goldman, 1970; Kirch, 2010; Hommon, 2013). Comparison of Contact-era Hawaiian social organization with other Polynesian archipelagos indicates that, at some point in its history, Hawai'i underwent a transformation that ruptured the genealogical connection between elite *ali'i* and common *maka'āinana* (Sahlins, 1992; Hommon, 1976, 1986). One spatial expression of this process was the establishment of *ahupua'a* land divisions where communities of *maka'āinana* were managed by an appointed official of the state government known as a *konohiki* (Hommon, 1976, 1986). A typical *ahupua'a* contains the full range of resources needed for subsistence and, at the time of European contact, functioned as a unit for the payment of tribute in kind and labor to a multi-tiered hierarchy of elite *ali'i*. These circumstances have led to a characterization of *ahupua'a* that highlights the management role of *konohiki* as collectors of tribute in isolated and self-sustained communities (e.g., Hommon, 2013; Kirch, 2010). However, within this broad characterization of the Contact-era *ahupua'a* there remains many questions potentially addressed by archaeological information. How deeply did this Hawaiian social transformation affect the lives of *maka'āinana*? Were tribute production and *konohiki* management a central part of *maka'āinana* life? Or, did they require *maka'āinana* to make relatively minor adjustments to a social life with deep roots in the past?

An important contribution to the study of these questions was made recently by McCoy et al. (2011), who modeled the distribution of volcanic glass from the Pu'uwa'awa'a source as overland transport across a cost surface and investigated technological attributes of the transported glass to argue that there was “unfettered access” (McCoy et al., 2011, 2547) to Pu'uwa'awa'a. In this view, Pu'uwa'awa'a volcanic glass was a common-pooled resource that was exchanged among *maka'āinana* free of control by *ali'i*. This finding contrasts with a preliminary, small-scale investigation of adze rock distribution that posits *ali'i* control over access to this material that becomes a source of economic power (Kirch et al., 2012). According to McCoy et al. (2011), it is possible to discover a mix of *maka'āinana* behaviors responsible for the distribution of Pu'uwa'awa'a volcanic glass, including direct access for people who lived close to the source, down-the-line exchange to a distance of a single day's travel overland, and direct access from more distant locations, perhaps involving transport of volcanic glass by canoe.

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http://dx.doi.org/10.1016/j.jasrep.2015.03.006
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Please cite this article as: Putzi, J.L., et al., Alternative models of volcanic glass quarrying and exchange in Hawai'i, Journal of Archaeological Science: Reports (2015), http://dx.doi.org/10.1016/j.jasrep.2015.03.006

This paper reports a new collection of volcanic glass recovered from Site 50–10–19–30173 located close to the Pu'uwa'awa'a source (Fig. 1) and attempts to build upon and strengthen the analysis carried out by McCoy et al. (2011). It does this by suggesting certain refinements to the technological analysis, by proposing alternative distribution routes to the overland cost surface, and by showing that the three component model, with separate components for varying distances from the source, can be replaced with a single distance decay model based on an exponential function. Exponential models have a strong theoretical and empirical foundation in geography (e.g., Haggett et al., 1977; Taylor, 1971) and their utility in the archaeological situation was established many years ago (Hodder, 1974; Renfrew, 1975, 1977). It is argued that systematic deviations from an exponential model indicative of directional trade are absent in the distribution of Pu'uwa'awa'a volcanic glass and that this provides strong support for the hypothesis of unfettered access. Finally, differences in the *chaînes opératoire* of volcanic glass and adze rock from the Mauna Kea quarry are briefly noted and the exponential model is recommended for investigating the distribution of adze rock so that a direct comparison with the distribution of volcanic glass can be achieved.

2. Description of Site 50–10–19–30173

Site 50–10–19–30173 was discovered during archaeological monitoring at the Kona Village Resort for a project to repair facilities damaged during the tsunami of March 11, 2011. Current building codes require utilities be placed underground; at the resort this entailed excavating a trench with a hoe ram through low portions of a lava flow. Although a large-scale geologic map of lava flows on Hawai'i Island (Wolfe and Morris, 1996) shows a 1500 year old *pāhoehoe* flow here and most of the interface between this older flow and an AD 1800–1801 *'a'ā* flow that partially overlies it has been obscured by development of the resort, inspection of sections exposed by the hoe ram confirms that this lava is a *pāhoehoe* member of the 1800–1801 flow and not part of the older *pāhoehoe* flow. Lava extended beneath the water table in most excavations, but at the inland end of the resort, about 400 m from the shoreline, the hoe ram exposed a calcareous coarse sand beach deposit that had been covered by the AD 1800–1801 lava flow (Fig. 2).

Close inspection of the trench face revealed unusual stratification within the beach deposit beneath the lava flow (Fig. 3). The basic stratigraphy consisted of four coarse calcareous sand layers, Contexts 104–107, underlying the AD 1800–1801 lava flow, which was designated Context 103 (Fig. 4). Context 104, immediately beneath the lava flow is a pale yellow layer of contact metamorphosed sandstone. Context 105 is a dark gray layer of thermally altered sand that contained a few traditional Hawaiian artifacts and marine shell whose colors lacked chroma due to exposure to extreme heat. Context 106 is a light brownish gray sand with numerous thin dark lenses that might represent organic-rich deposits carbonized by the lava flow. It contained the bulk of the traditional Hawaiian artifacts, none of which show any obvious effect of exposure to extreme heat. Context 107, at the base of excavation, is culturally-sterile, very pale brown sand.

Also present were very dark grayish brown irregularly-shaped lenses, two of which, Contexts 116 and 117, are shown on Fig. 4. These lenses are located at the base of Context 106 and extend into the basal sand, Context 107. It was not possible to determine whether these contexts were cultural features or by-products of heat from the lava flow, perhaps the burned root systems of vegetation. The cultural content of the lenses was similar to Context 106.

Remnant cultural deposits located in the base of the trench and beneath the lava flow in the sides of the trench were excavated with a trowel and the excavated sediments were passed through 0.125 in. mesh screen to facilitate identification and collection of small items of cultural material. These excavations were made difficult by the degree to which the hoe ram had disturbed deposits within the trench and safety issues associated with undermining the lava flow. These challenging conditions

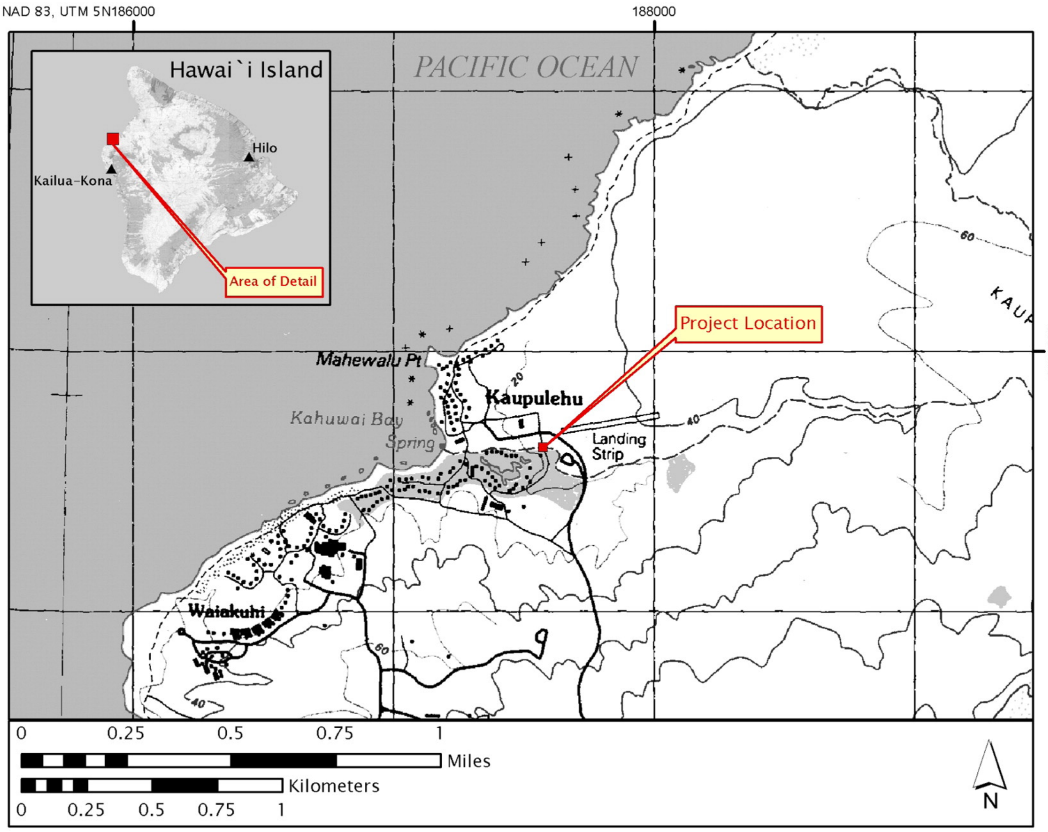

Fig. 1. Project location on a portion of a USGS quadrangle map.

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Fig. 2. Photograph of the utility trench showing the beach sand deposit capped by the 1800–1801 lava flow. The scale, which sits on top of the lava flow, is marked in 10 cm increments.

and the limited extent of the excavations made it impossible to characterize confidently the archaeological events responsible for the cultural deposits. A general impression based on field observation of poorly sorted coarse sand is that the deposits were laid down close to the shoreline, likely seaward of more substantial cultural deposits along the back beach.

Nevertheless, 166 traditional Hawaiian artifacts were collected and cataloged during the excavations, including 138 pieces of volcanic glass, eight pieces of modified mammal bone, five echinoid spine abraders, three coral abraders, three basalt abraders, three mammal bone fishhooks, two adzes, two pieces of modified shell, one piece of basalt debitage, and a cowry shell octopus lure (Fig. 5). No historic period artifacts were recovered from sediments beneath the lava flow.

Charcoal samples collected from Contexts 105, 106, and 116 beneath the lava flow were identified to the lowest possible taxonomic level by Gail Murakami of the International Archaeological Research Institute Wood Identification Laboratory. Thirteen native and Polynesian introduced plants were identified (Table 1). Historically introduced plants were not identified in the charcoal.

Two pieces of charcoal identified as the Polynesian introductions *kī* and *kukui* were sent to Beta Analytic, Inc. for dating with AMS. After pre-treatment at the laboratory, the sample of *kukui* nutshell was found to be incompletely carbonized; it returned a modern date. The charcoal identified as *kī* wood was analyzed as Beta-376428 and returned a conventional radiocarbon age of 250±30 bp. This age determination was calibrated with the BCal software (Buck et al., 1999) using a recent atmospheric calibration curve (Reimer et al., 2013) and a single phase model with a *terminus ante quem* of AD 1800, which corresponds to the known age of the lava flow that sealed the site: $\alpha_1 > \theta_1 > \beta_1 =$ AD

Fig. 3. Photograph of the stratification showing the 1800–1801 lava flow (top) and the discoloration of the sand due to the heat of the lava flow. The scale is marked in 10 cm increments.

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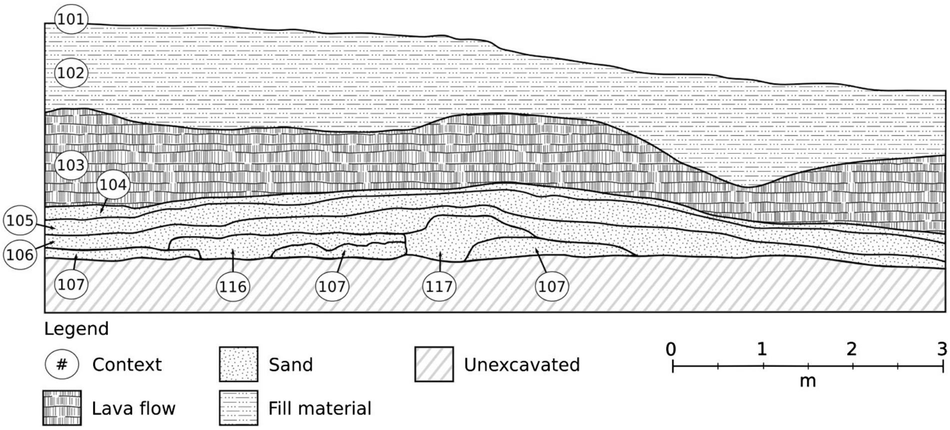

Fig. 4. Stratigraphic profile of the east face of the utility trench showing identified contexts. Contexts 104–107, 116, and 117 represent a sand beach deposit capped by a lava flow, Context 103, in AD 1800–1801. Context 102 is fill topsoil laid down for resort development; its surface, Context 101, supports various resort facilities today.

1800, where α_1 and β_1 are the start and end dates of the single phase, respectively, and θ_1 represents the true calendar age of the *kī* wood charcoal. The calibrated estimate of θ_1 indicates that the *kī* plant grew for a relatively short time in AD 1530–1799 (95% probability), probably at the later end of this range, AD 1640–1799 (68% probability).

3. Technological analysis of volcanic glass assemblages

The 138 pieces of volcanic glass recovered from the beach sand deposit under the lava flow include 132 complete and partial flakes and six pieces of angular debris. No cores were recovered. There are 105 complete flakes, the distal ends of 23 flakes, the proximal ends of two flakes, and two medial sections. Two flakes each exhibit two flake bulbs indicative of bipolar reduction, but the rest have a single bulb of percussion. Cortex is present on 68 flakes, eleven of which have primary cortex over the entire dorsal surface and 57 have secondary cortex mixed with flake scars. 64 flakes have no, or tertiary, cortex. The lengths of complete flakes range from 6 to 31 mm; the median complete flake length is 15.3 mm. Flakes with secondary cortex tend to be longer than flakes with either primary or tertiary cortex (Fig. 6).

McCoy et al. (2011) carried out technological analyses designed to investigate the use lives of volcanic glass cores in an effort to identify down-the-line exchange. They reason that, in the presence of down-the-line exchange, sites far from the source will yield assemblages of

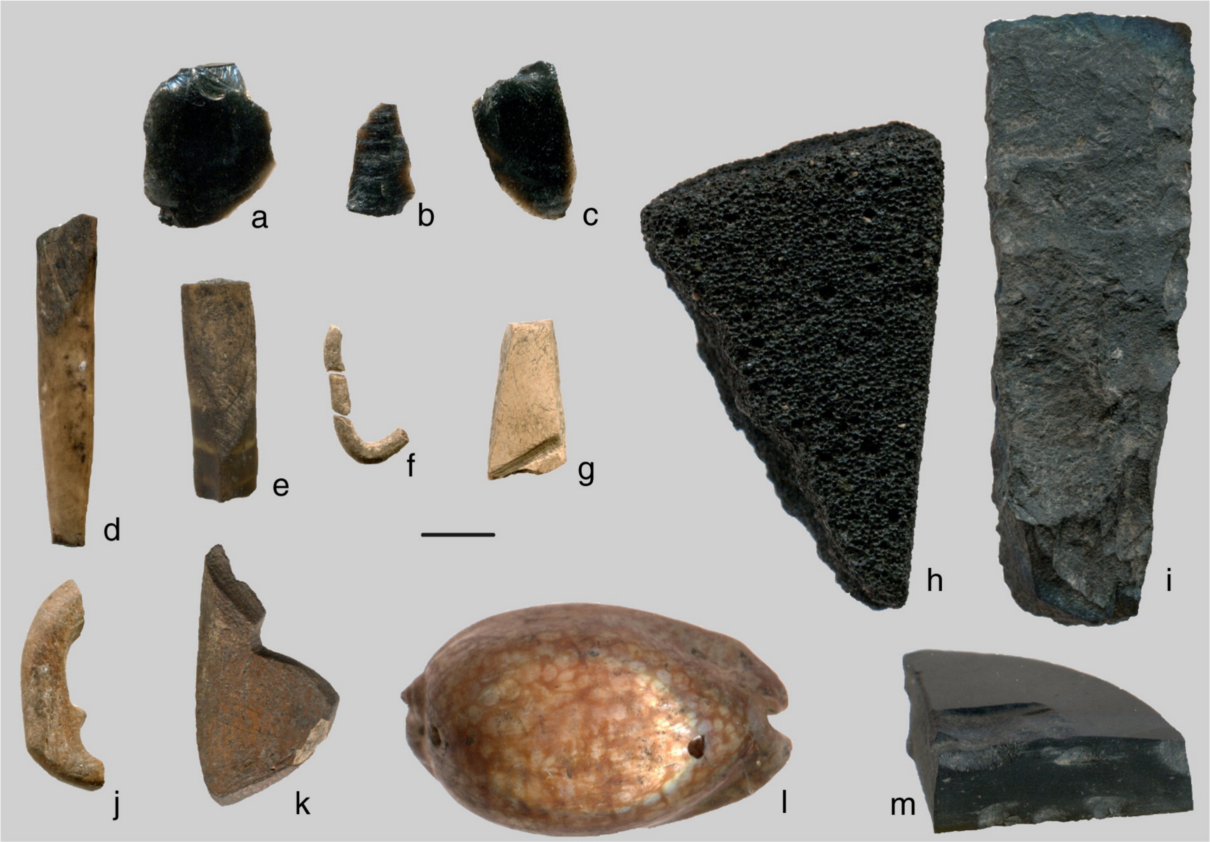

Fig. 5. Traditional Hawaiian artifacts recovered from beneath the lava flow: *a*–*c*, Pu'uwa'awa'a volcanic glass flakes; *d*, *e*, echinoid spine abraders; *f*, bone one-piece fishhook fragments; *g*, mammal bone manufacturing waste; *h*, vesicular lava abrader; *i*, basalt adze; *j*, bone fishhook fragment with barb; *k*, bone fishhook tab; *l*, cowry shell octopus lure. *m*, highly-polished basalt adze fragment. The scale bar is 1 cm.

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Table 1
Taxa identified from charcoal.

Family	Taxon	Name	Habit	Origin
Agavaceae	cf. *Cordyline fruticosa*	*kī*	Shrub	Poly. intro.
Apocynaceae	cf. *Rauvolfia sandwicensis*	*hao*	Tree	Native
Asteraceae	cf. *Bidens* sp.	*ko'oko'olau*	Shrub	Native
Ebenaceae	*Diospyros sandwicensis*	*lama*	Tree	Native
Euphorbiaceae	*Aleurites moluccana*	*kukui*	Tree	Poly. intro.
Euphorbiaceae	*Chamaesyce* sp.	*'akoko*	Shrub–tree	Native
Malvaceae	*Hibiscus tiliaceus*	*hau*	Shrub–tree	Native
Myrtaceae	*Metrosideros polymorpha*	*'ōhi'a lehua*	Tree	Native
Pandanaceae	*Pandanus tectorius*	*hala*	Tree	Native
Pittosporaceae	cf. *Pittosporum* sp.	*hō'awa*	Tree	Native
Rubiaceae	*Canthium odoratum*	*alahe'e*	Shrub–tree	Native
Rubiaceae	cf. *Coprosma* sp.	*pilo*	Shrub–tree	Native
Sapindaceae	*Dodonaea viscosa*	*'a'ali'i*	Shrub-tree	Native
Sapindaceae	cf. *Dodonaea viscosa*	*'a'ali'i*	Shrub–tree	Native

volcanic glass that reflect the use of well-used cores as raw material. In this situation, it is expected that flake size will be small, the frequency of cortex will be low, and wasted cores will be common.

Based on six assemblages ranging from 7.41 to 18.79 h round trip duration to and from Pu'uwa'awa'a, they found an exponential rise in the proportion by weight of wasted cores (McCoy et al., 2011, 2555). The absence of cores in the assemblage from Site 50–10–19–30173, which is closer to Pu'uwa'awa'a than any of the other assemblages, generally supports this finding. However, there are two concerns. First, the exponential rise in the proportion by weight of wasted cores was established with a relatively small number of sites located near Pu'uwa'awa'a and excludes sites more distant from the source. The assemblage from Site 50–Ha–B21–20, with a nearly 40-hour round trip duration, yielded a high proportion of wasted cores, consistent with the general pattern but less than predicted by the exponential function. The other assemblage from Sites 50–Ha–B22–65 and –84 with a 38.39-hour round trip duration, yielded an unexpectedly low proportion of wasted cores, consistent with a round trip travel time less than 11 h. Perhaps more important, however, most of the variability in the proportion of wasted cores comes from assemblages with 12 or fewer pieces of volcanic glass (Fig. 7). The small size of these samples might have introduced variability that is not present in the underlying populations of volcanic glass at these sites.

McCoy et al. (2011, 2555) found that volcanic glass artifacts with cortex were relatively common at three sites near Pu'uwa'awa'a and nearly absent at three sites farther than 11 h of round trip travel time. The relatively high proportion of flakes with cortex from Site 50–10–19–30173, which is close to Pu'uwa'awa'a, lends support to this observation. However, this pattern breaks down if two more distant sites are included. If all of the assemblages for which cortex information is available are plotted, rather than just the close ones, then there appears to be no association between the proportion of artifacts with cortex and round trip duration (Fig. 8). The small sample sizes from several sites yield a regression line with a large standard error. The lack of sites with round trip travel times between 19 and 38 h means the small assemblages distant from Pu'uwa'awa'a wield undue influence on the slope of the regression line. When these distant sites are included, no simple relationship between distance from Pu'uwa'awa'a and incidence of cortex is apparent.

Using assemblages from four sites close to Pu'uwa'awa'a, McCoy et al. (2011, 2556) found a regular decline in the "average" (presumably mean) length of flakes with distance from Pu'uwa'awa'a. The mean flake length at Site 50–10–19–30173 is somewhat shorter than predicted by the regression line formula (McCoy et al., 2011, Fig. 9), and this has the effect of lessening the slope of the regression line. If distant sites are included, then the slope of the regression line is positive (Fig. 9). Again, the small number of assemblages, the small sizes of several of them, and the lack of sites with round trip travel times between 19 and 38 h all have an effect on the analysis. In any event, there is no clear relationship between mean flake length and distance from Pu'uwa'awa'a. The small number of assemblages and the small sizes of many of them make confident inferences impossible.

4. Distribution of Pu'uwa'awa'a volcanic glass on Hawai'i Island

In hand sample the volcanic glass flakes from Site 50–10–19–30173 exhibit the dark olive green color indicative of a Pu'uwa'awa'a source. The volcanic glass pieces were analyzed with EDXRF at the University of Hawai'i at Hilo (Lundblad et al., 2008, 2011). The elemental composition of the volcanic glass pieces when compared using trace element ratios of Y, Sr, and Zr indicates that the volcanic glass pieces recovered from Site 50–10–19–30173 all derived from the trachytic Pu'uwa'awa'a source (Fig. 10).

The distribution of Pu'uwa'awa'a volcanic glass away from the source was first investigated by McCoy et al. (2011), who computed with ArcGIS 9.3.1 software cost surface overland routes and round trip travel times between Pu'uwa'awa'a and 19 archaeological sites with collections of 15–489 volcanic glass pieces (McCoy et al., 2011, Table 4) (Fig. 11). Round trip travel times varied from 7.41 h to 41.23 h. When the percentage frequency of Pu'uwa'awa'a volcanic glass in 15 assemblages from sites close to the source was plotted against round trip travel time, a strong linear relationship was found (McCoy et al., 2011, 2553). This linear relationship does a good job of predicting the proportion of Pu'uwa'awa'a volcanic glass in the Kona Village assemblage. Four sites with round trip travel times greater than 22 h were considered outliers and were excluded from the spatial analysis.

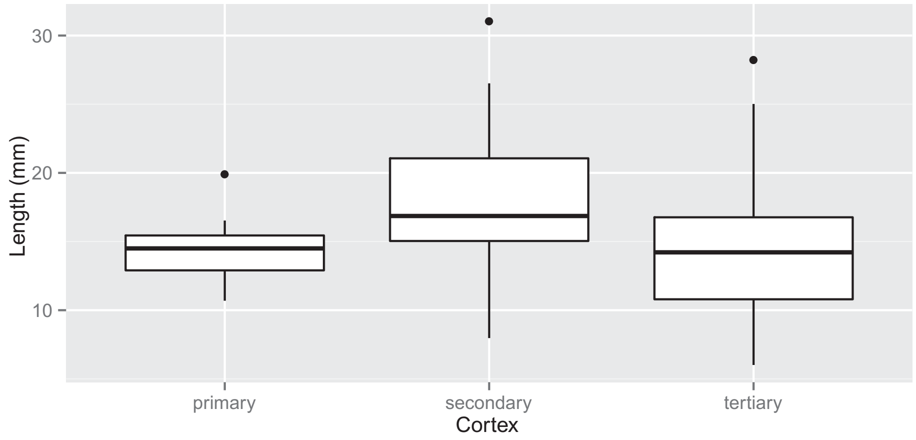

Fig. 6. Boxplot of complete volcanic glass flake lengths for different types of cortex.

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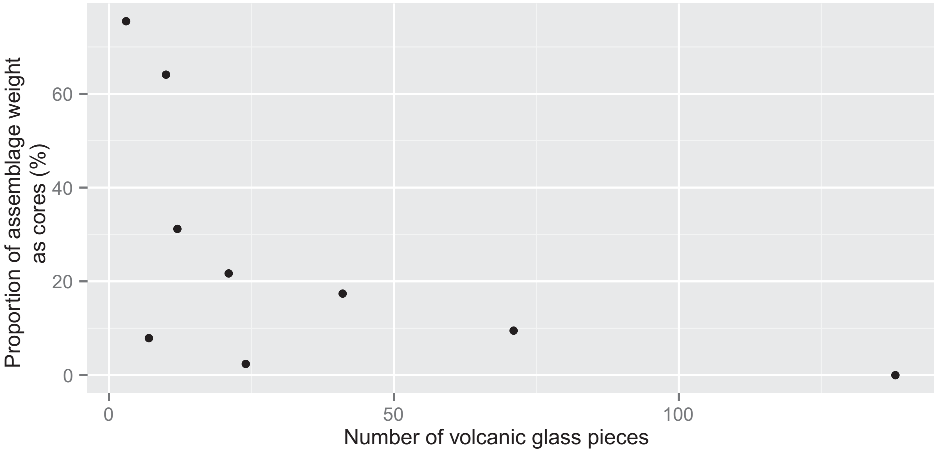

Fig. 7. The proportion of assemblage weight as cores varies with the size of the assemblage. Note that most of the variability in this measure is introduced by small assemblages.

The linear relationship between percentage frequency of Pu'uwa'awa'a volcanic glass and round trip travel time breaks down when distant sites are included (Fig. 12). It underestimates the proportion of Pu'uwa'awa'a glass close to the source, and overestimates it for round trips longer than about 15 h. An exponential curve, where a straight line is fitted to the relationship between round trip travel time and the logarithm of percentage frequency of Pu'uwa'awa'a volcanic glass, does a better job, although it too tends to underestimate the proportion of Pu'uwa'awa'a glass close to the source (Fig. 12). Renfrew (1977, 78) identified positive residuals close to the source as evidence of a "supply zone", however, Hodder (1974, 182) noted that this pattern is characteristic of situations where the movement of materials away from a source result from a random walk process.

Although a cost surface provides an intuitively attractive way to determine effective distances between two points, in practice it relies on proprietary software that requires considerable training to use properly, and which is likely to be unavailable to many field archaeologists. An alternative model that is simpler to use connects the Pu'uwa'awa'a source to sites with volcanic glass assemblages with straight lines that can be measured by hand on a USGS quad map (Fig. 13). The straight line model yields an exponential decay curve with distance from the source, but the fit is not as good as the cost surface (Fig. 14).

McCoy et al. (2011, 2547) note the possibility that transport of volcanic glass to sites distant from Pu'uwa'awa'a might have been by canoe rather than overland. Accordingly, a model of volcanic glass distribution by canoe transport was investigated using a model that posits use of Site 50–10–19–30173 at Kahuwai Bay as a depot. Either residents of the village at Kahuwai Bay collected volcanic glass cores from Pu'uwa'awa'a and brought them to the coast to exchange with canoe travelers from other parts of Hawai'i Island, or canoe travelers put ashore at Kahuwai Bay and accessed Pu'uwa'awa'a from there with a hike that took the better part of a day. Coastal distances from Site 50–10–19–30173 to the coastal locations closest to other sites with volcanic glass assemblages were derived by measuring the length of coastline with GIS software (Fig. 15). An exponential distance decay curve fits this model better than the two overland transport models, which suggests that transport of volcanic glass by canoe might have been important for people living relatively close to Pu'uwa'awa'a, as well as those living far away (Fig. 16).

5. Discussion

McCoy et al. (2011) concluded that Pu'uwa'awa'a volcanic glass was a common pooled resource to which there was "unfettered access" in traditional Hawaiian times, both through the exercise of a right not to be excluded from direct access to the source and through down-the-line exchange of volcanic glass cores outside the purview of *ali'i* control. They support this conclusion with a linear regression on the relationship between the contribution of the Pu'uwa'awa'a source to site assemblages of volcanic glass and the site to source round trip travel time as determined by cost surface analysis using GIS software for a subset of sites close to Pu'uwa'awa'a. The linear regression calculated on the

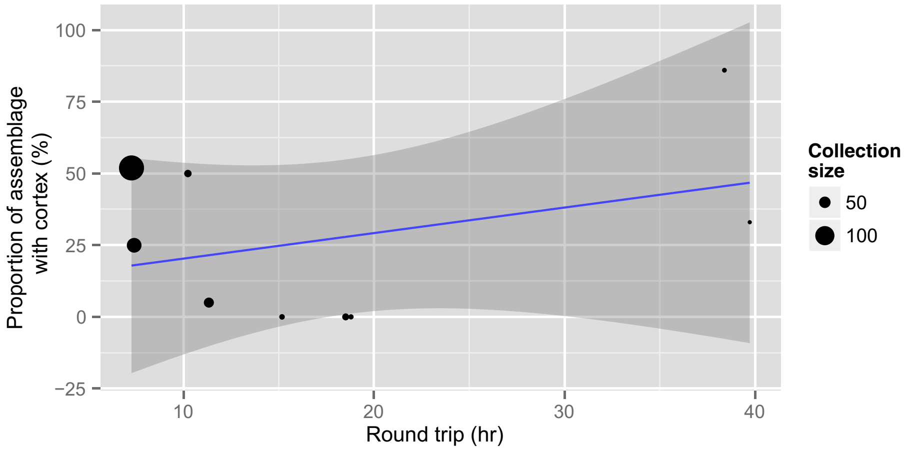

Fig. 8. Proportion of assemblage with cortex as a function of round trip duration from Pu'uwa'awa'a. The regression line was computed using the rlm method of Venables and Ripley (1994). The shaded area is the 95% confidence interval for the regression.

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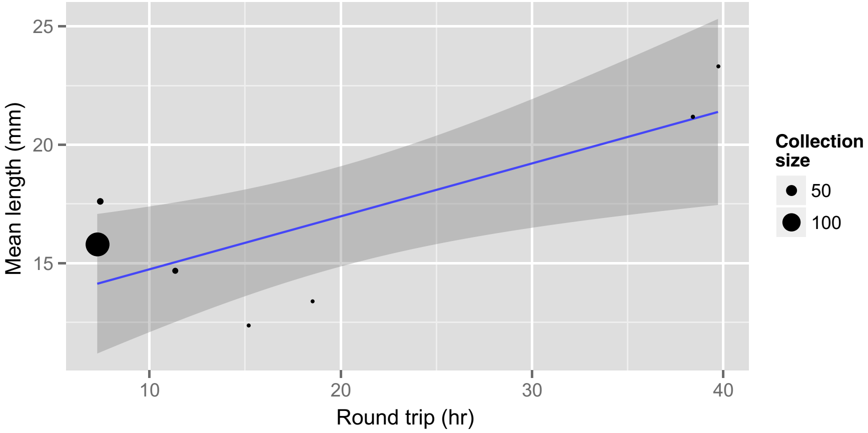

Fig. 9. Mean flake length as a function of round trip duration to and from Pu'uwa'awa'a. The linear regression line was computed using the rlm method of Venables and Ripley (1994). The shaded area is the 95% confidence interval for the regression.

untransformed variables fits well for sites located close to Pu'uwa'awa'a, but it intersects the x-axis at a round trip travel time of about 24 h McCoy et al. (2011, 2554) and sites with Pu'uwa'awa'a volcanic glass more distant from the source, where the model predicts Pu'uwa'awa'a volcanic glass is absent, are excluded from the spatial and technological analyses as outliers.

McCoy et al. (2011) do not discuss the decision to carry out the regression on untransformed variables, which assumes that the fall-off in the contribution of Pu'uwa'awa'a volcanic glass to site assemblages is dependent only on change in distance (Renfrew, 1977; Hodder, 1974). Based on numerous empirical studies, archaeologists and geographers have found that variability in interaction is dependent not only on distance, but also on the transferability and relative value of the materials being transported (Hodder, 1974; Haggett et al., 1977). When these other factors are taken into account, the best fit to the untransformed variables is a curved line that drops rapidly close to the source and then levels out as distance increases (Haggett et al., 1977; Renfrew, 1977; Taylor, 1971). The demonstration that the distribution of Pu'uwa'awa'a volcanic glass can be described with an exponential curve using alternative measures of distance, including straight line overland, cost surface overland, and coastal transport from a depot at Kahuwai Bay, indicates that identification by McCoy et al. (2011) of distant site outliers is likely an artifact of model selection, rather than a reflection of the factors underlying the observed distribution of volcanic glass. Factors other than distance are also responsible for the distribution of volcanic glass away from the Pu'uwa'awa'a source.

What are these other factors? Transferability plays a major role with bulky or heavy items; the canonical archaeological examples are the distribution of Romano-British roofing tiles around Cirencester and several varieties of coarse pottery for which distributional studies have been completed (Hodder, 1974, 179–182). In contrast, Pu'uwa'awa'a volcanic glass nodules are small and light; transferability should not constrain their distribution away from the source. Rather, it seems likely that the relative value given to Pu'uwa'awa'a volcanic glass in traditional Hawai'i was a factor in its distribution away from the source. Geographers and others have noted that the value of a material is related to the shape of the drop-off curve. Materials that are highly valued are used far from the source and are distributed widely. They yield drop-off curves with low slopes and long tails. In contrast, low-valued materials are used near to the source and are not distributed widely. They yield drop-off curves with high slopes and short tails. The exponential drop-off of Pu'uwa'awa'a volcanic glass indicates that it was highly valued in traditional Hawai'i.

Because the exponential curve does not intersect the x-axis, there is no upper bound to the distribution and no way to predict the full size of the distribution field. Thus, geographers use the concept of mean field to measure and compare the sizes of distribution fields (Haggett et al., 1977, 48–50). The mean field is calculated here as the point along the exponential curve where the proportional change of distance exceeds the proportional change in the percentage of Pu'uwa'wa'a volcanic glass in an assemblage. Calculation of the mean field indicates that the value of Pu'uwa'awa'a volcanic glass in traditional Hawai'i was

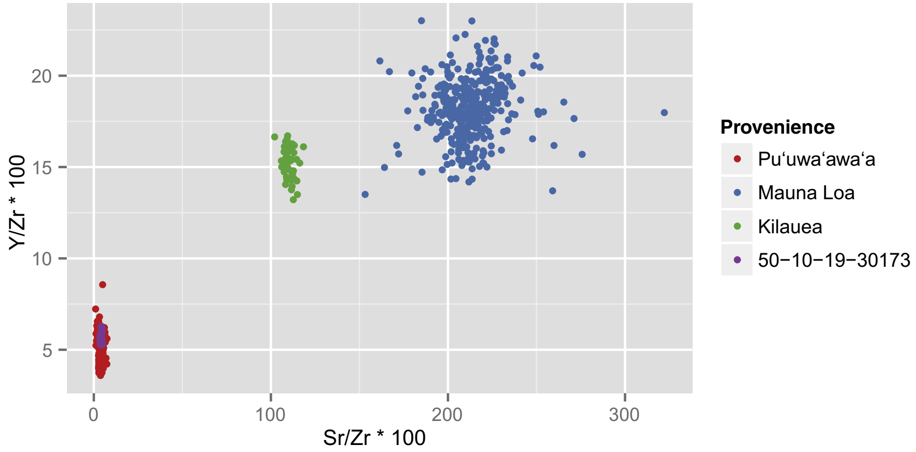

Fig. 10. Trace element ratios of Kona Village volcanic glass artifacts compared to volcanic glass from Pu'uwa'awa'a, Klauea, and Mauna Loa (after Lundblad et al., 2013, Fig. 2).

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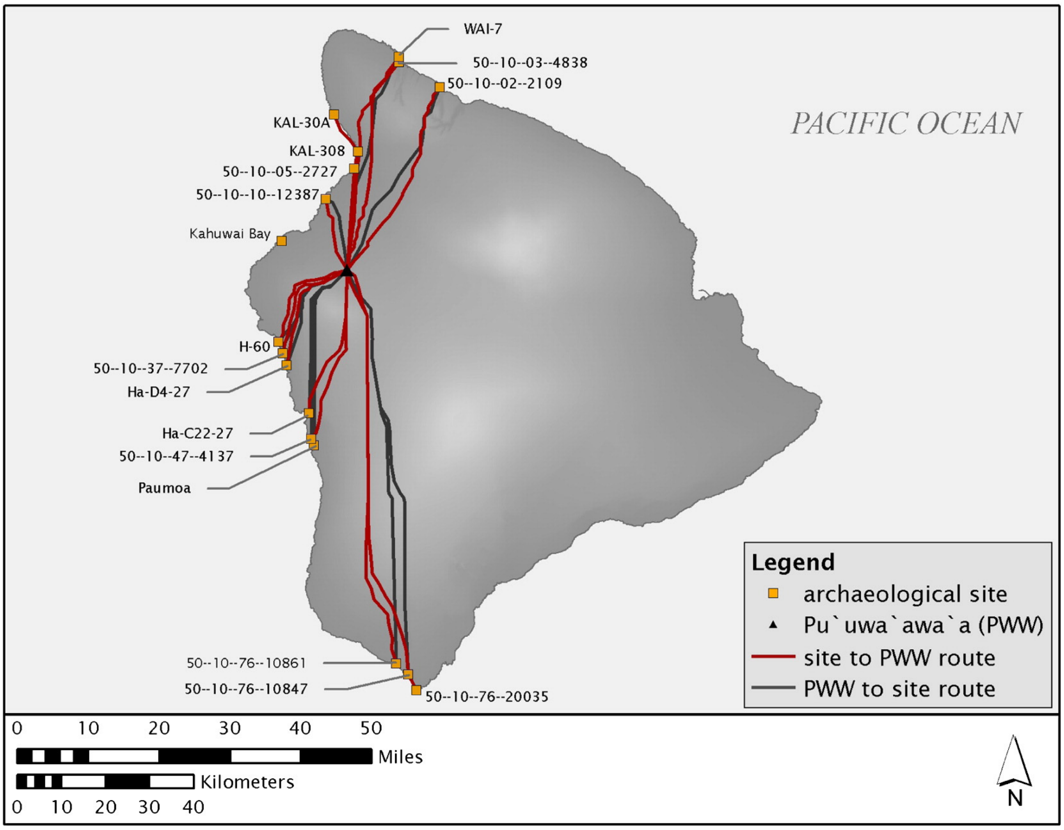

Fig. 11. Cost surface overland routes to and from Pu'uwa'awa'a. Adapted from McCoy et al. (2011, fig. 6). Note that the routes to and from Kahuwai Bay and Site 50–10–19–30173 are not shown.

such that it was transported regularly to sites within a radius of about 21 h round trip travel time or 46 km straight line overland from Pu'uwa'awa'a, or a distance of about 63 km along the coast from Kahuwai Bay. Past the mean field, a small quantity of Pu'uwa'awa'a volcanic glass is expected at sites as far away as 41 h round trip travel time or 98 km straight line overland from Pu'uwa'awa'a, or 127 km along the coast. Future work on Hawai'i Island, especially in the windward districts of Hamakua, Hilo, and Puna, is likely to expand the range of sites where Pu'uwa'awa'a volcanic glass is known to have been used and deposited.

Fitting an exponential curve to the full data set makes it possible to distinguish the effects of directional trade, in which certain sites function as central places that receive materials directly from the source, regardless of distance, and from which the materials are redistributed to nearby sites that don't receive them directly from the source (Renfrew, 1977, 85–87). Directional trade is typically associated with redistribution of materials under the direction of some central control (Renfrew, 1975, 48). An investigation into the distribution of obsidian within the Maya sphere lends empirical support to the theoretical expectation that one effect of directional trade is to decrease the fit of

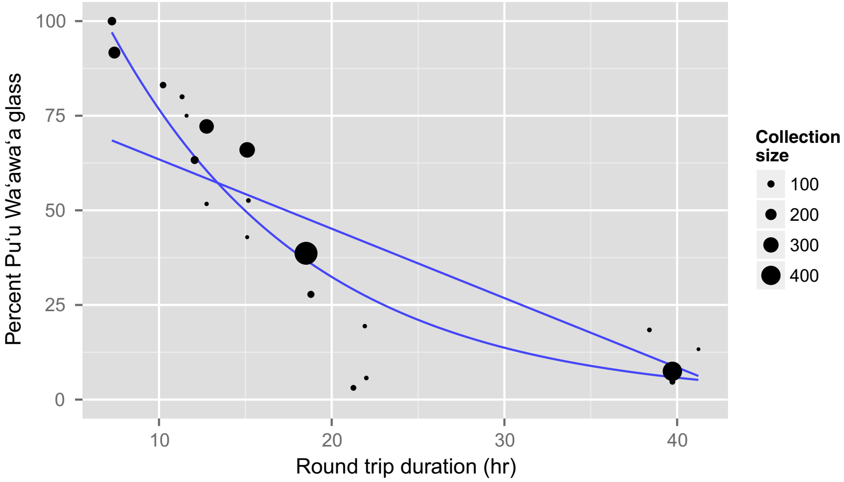

Fig. 12. Exponential and straight line fits for the percentage frequency of Pu'uwa'awa'a volcanic glass and overland round trip travel times computed with a cost surface model. The exponential function is $I = exp(5.20 - 0.09^{*}D)$ and the linear function is $I = 81.80 - 1.83^{*}D$, where I = percent Pu'uwa'awa'a glass and D = round trip duration in hours. The value of R^2 for the exponential function is 0.56.

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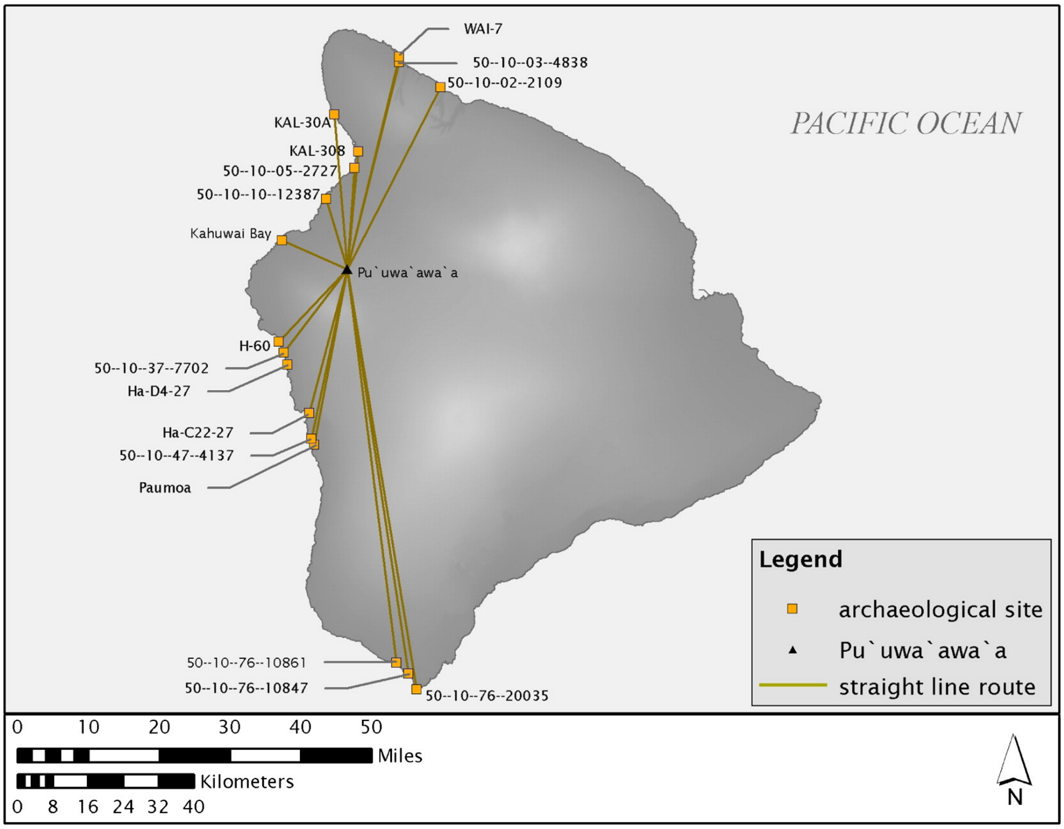

Fig. 13. Straight line routes from Pu'uwa'awa'a to archaeological sites with volcanic glass assemblages.

an exponential curve to the distributional data (Sidrys, 1977). So far, deviations from the exponential curve that might indicate directional trade are not evident in the Pu'uwa'awa'a volcanic glass data. The distribution of Pu'uwa'awa'a volcanic glass appears to have taken place in the context of traditional social relationships independent of the political hierarchy.

The important observation that Pu'uwa'awa'a volcanic glass was not distributed outside Hawai'i Island (McCoy et al., 2011, 2552) indicates that Pu'uwa'awa'a volcanic glass wasn't valued so highly that it was transported to other islands. In this respect, the distribution of Pu'uwa'awa'a volcanic glass contrasts with Mauna Kea adze basalt, which has been identified recently from six sites on Maui Island, including an elite residence and three religious structures (Kirch et al., 2012), and perhaps as far afield as O'ahu Island (Mills and Lundblad, 2014, 34). The distribution of non-local basalt in the Maui Island sites was interpreted as evidence for directional trade where "access to and distribution of these stone resources was controlled by elites" (Kirch et al., 2012, 1060). Given this difference, it is useful to distinguish the *chaînes opératoire* for volcanic glass and adze rock by comparing evidence for the organization of production at Pu'uwa'awa'a and the Mauna Kea adze quarry. The area around Pu'uwa'awa'a has been described as barren of traditional Hawaiian habitation and

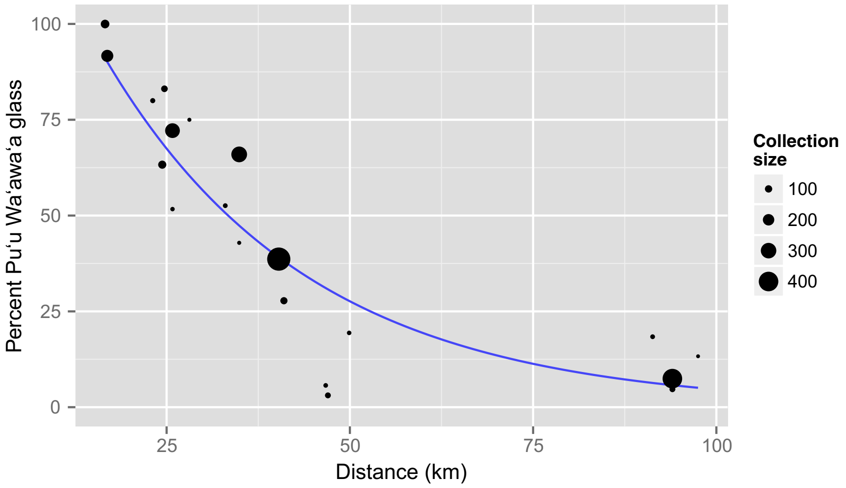

Fig. 14. Exponential distance decay function for the straight line overland model: $I = exp(5.10 - 0.04^{*}D)$, where I = percent Pu'uwa'awa'a glass and D = distance in km. The value of R^2 for the exponential function is 0.53.

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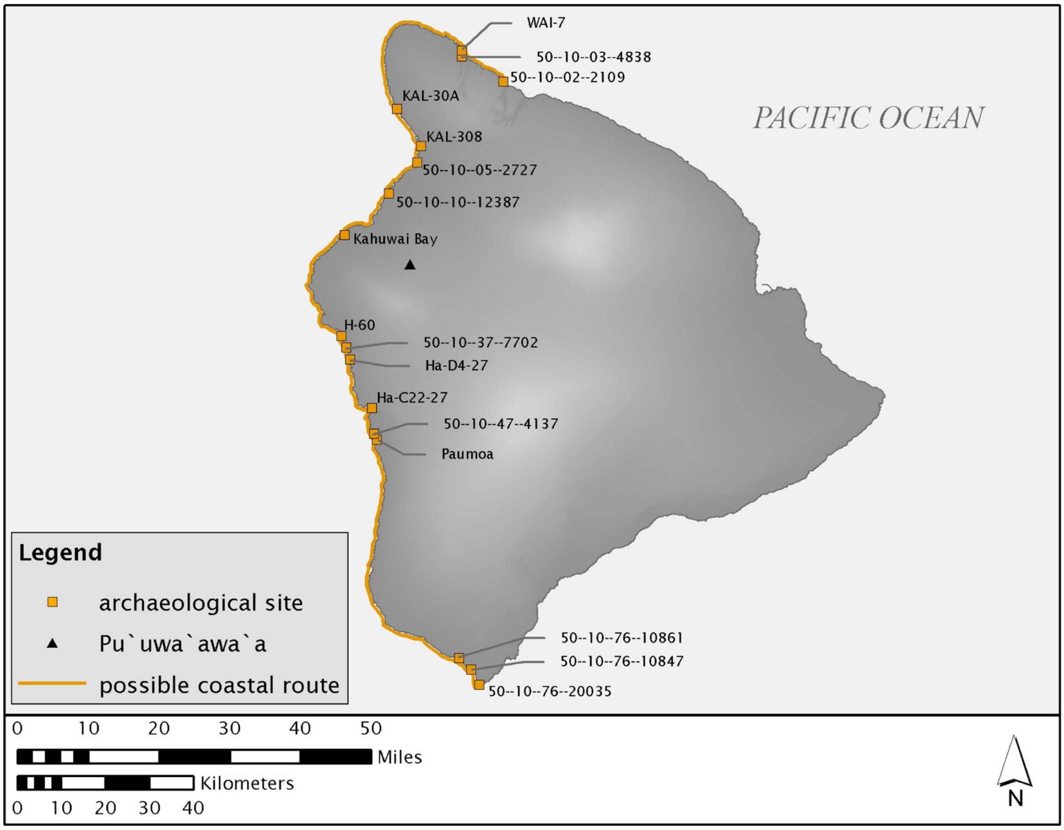

Fig. 15. Coastal routes from Pu'uwa'awa'a with a depot at Kahuwai Bay.

agriculture, and the source of volcanic glass nodules on the north face of Pu'uwa'awa'a hill lacks a formal quarry (McCoy et al., 2011, 2548–2549). In contrast, the Mauna Kea adze quarry has a multitude of shrines; in fact, shrines are the most common type of architectural feature at the quarry. It has been argued that ritualization of production at the quarry, including rites of passage sites used to initiate apprentices into an adze-makers' guild (McCoy, 1999), is strong evidence for adze makers having been specialists attached to *ali'i* (McCoy et al., 2010).

These preliminary observations on the differences between the ritualized production and consumption of Mauna Kea adze rock, which appears to have been exchanged through directional trade, and the exchange of Pu'uwa'awa'a volcanic glass, the raw material for an expedient tool that was exchanged through traditional social relations, are based on the current state of distributional data (Mills and Lundblad, 2014), which are deficient in several respects, including (i) sample sizes that are too small to support confident inferences, (ii) patchy spatial coverage with large gaps between some sites and uncertain distributional boundaries, and (iii) an almost complete lack of chronological control.

The low cost and non-destructive nature of EDXRF and the confidence with which the technique is able to identify Pu'uwa'awa'a volcanic glass make it possible to model traditional Hawaiian exchange in an

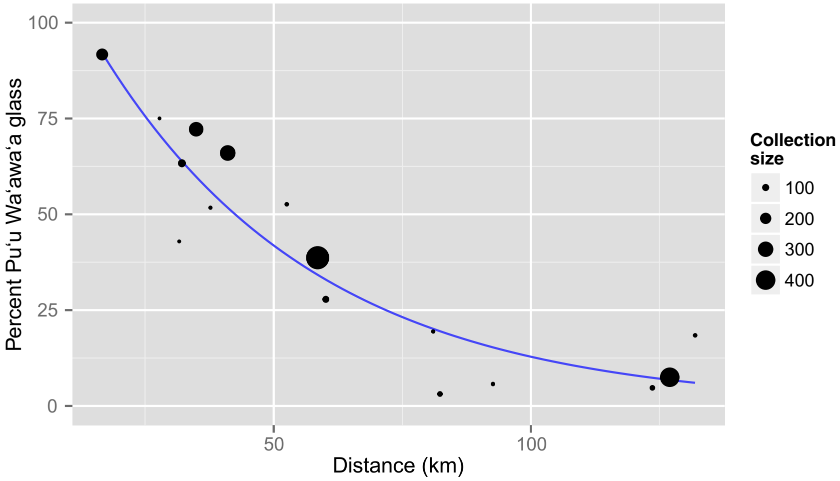

Fig. 16. Exponential distance decay function for the coastal model: $I = exp(4.92 - 0.02^{*}D)$, where I = percent Pu'uwa'awa'a glass and D = coastal distance in km. The value of R^2 for the exponential function is 0.65.

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analytically useful way. However, at this early stage of investigation the small sizes of many volcanic glass collections restricts the information they have yielded. Using a ruler and a suitable map of Hawai'i Island, the straight-line method described above conveniently produces an expected value, p, for the percentage of Pu'uwa'awa'a volcanic glass at a site. Given this information, a problem-oriented excavation strategy can be designed to yield a sample size, n, that establishes the observed percentage within a specified precision using the formula for the standard deviation of a binomial distribution, $\sqrt{npq}$, where $q = 1 - p$.

Technological analyses play a potentially important role in determining the nature of volcanic glass exchange, but their promise has yet to be fulfilled, in part because relatively few sites have been analyzed in this way and sample sizes at the sites that have been analyzed are small. In addition, the technological attributes chosen for study might be refined. It is recommended that observations of cortex on whole flakes distinguish primary, secondary, and tertiary cortex. Using the proportion of each cortex type at Site 50–10–19–30173 as a baseline for a site with direct access to the source, it is expected that down-the-line exchange will yield drop off curves that are steepest for primary cortex and flattest for tertiary cortex. This pattern should be relatively easy to distinguish from the expected pattern yielded by direct access, where the wide distribution of fresh cores should yield drop off curves that are consistent across cortex types. Alternatively, a more labor intensive method might be used (Ditchfield et al., 2014).

Equally pressing is the need to track change over time (Mills and Lundblad, 2014, 36). The volcanic glass assemblages analyzed by McCoy et al. (2011) were collected in the 1960's through the 1980's before Hawaiian archaeologists were able to distinguish suitable dating materials and their ages cannot be estimated with confidence with the information at hand. Similarly, Lass (1994) attempted to chart change over time in the distribution of Mauna Kea basalt with assemblages that were insecurely dated. In addition, quarrying activities at both sources are difficult to date. The lack of a formal quarry at Pu'uwa'awa'a deprives archaeologists of a site to date and dates on unidentified charcoal with a potential for in-built age is the basis for the chronology of the Mauna Kea adze quarry (McCoy et al., 2009). Thus, the histories of the Pu'uwa'awa'a volcanic glass quarry and the Mauna Kea adze quarry—when they were discovered and how their use and the distribution of their products grew and perhaps declined—remain to be investigated with well-dated assemblages.

6. Conclusions

The exponential fall-off of Pu'uwa'awa'a volcanic glass with distance from source at archaeological sites on Hawai'i Island indicates a resource that was highly valued in traditional Hawai'i. The lack of evidence for directional trade supports the inference developed by McCoy et al. (2011) that Pu'uwa'awa'a volcanic glass was a common pooled resource distributed through traditional social relations outside the purview of elite control. The distribution of Pu'uwa'awa'a volcanic glass contrasts with preliminary indications that Mauna Kea adze rock was distributed by directional trade. The cultural elaboration of adze production on Mauna Kea contrasts strongly with the lack of evidence for similar elaboration at Pu'uwa'awa'a.

Alternative models of Pu'uwa'awa'a volcanic glass distribution cannot distinguish overland transport from transport by canoes, given the data at hand.

Future work should fill gaps in the known distribution of Pu'uwa'awa'a volcanic glass and define the limits of its distribution on Hawai'i Island. In addition, more detailed technological analyses are needed to distinguish down-the-line exchange from direct access.

Acknowledgments

The authors thank Mark D. McCoy, Tim Rieth, Marshall Weisler, Patrick C. McCoy, Andy Howard, and an anonymous reviewer for many useful comments on drafts of the paper. Mike Vitousek of the Hawai'i Historic Preservation Division required the archaeological monitoring that led to the discovery of Site 50–10–19–30173. Frank Trusdell, USGS, spent considerable time and effort identifying the AD 1800–1801 lava flow. Fieldwork was supported by Hualālai Resort and especially its staff members Jay Uyeda and Leina'ala Lightner. Any errors that remain are the responsibility of the authors.

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