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EIGHT MILLION POINTS PER DAY: ARCHAEOLOGICAL IMPLICATIONS OF LASER SCANNING AND THREE-DIMENSIONAL MODELING OF PU‘UKOHOLĀ HEIAU, HAWAI‘I ISLAND

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Recent applications of three-dimensional modeling in archaeology have become more widespread in recent years for site-based and landscape approaches. The authors perform a three-dimensional analysis of Pu‘ukoholā Heiau, using data collected with a Cyrax laser scanner. By examining the three-dimensional model, surface area and volumetric calculations are made. These calculations are used to estimate labor input based on experimental data collected in a previous study of excavated Maui heiau and producing similar results without need for excavation.

KEY WORDS: Hawaiian archaeology, heiau, laser scanning, three-dimensional modeling

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Especially within the last decade, the adoption of various forms of technology has improved archaeological survey techniques with the use of tools such as reflectorless total stations, remote sensing, global positioning systems (GPS), geographic information systems (GIS), and other computer programs. The accuracy and precision of these tools has been recognized for both site-based and landscape approaches, and they have become commonplace in archaeological survey worldwide.

The recent adoption of three-dimensional (3-D) laser scanning and computer modeling provides an additional means for accurate and precise analysis of 3-D archaeological features and landscapes (see Lock 2000; Longley and Batty 2003). The implementation of such tools provides a methodology that is more precise and accurate than manual survey methods in the recording of such features. By utilizing 3-D modeling, archaeologists can examine the nature of surface remains without performing extensive excavation of archaeological features. Additionally, this methodology provides a digital record of features that can be reexamined later in time, which is important in terms of long-term preservation and conservation measures.

We have applied this technology at Puʻukoholā Heiau in the South Kohala District of Hawaiʻi Island. This massive *luakini heiau* (sacrificial temple) was built by Kamehameha I in the early post-Contact period (A.D. 1790 to 1791), and it has been well documented as a result. A considerable body of information in the form of ethnohistoric, historic, and archaeological accounts has been complied for this heiau, which is well preserved and has been managed by the National Park Service since the early 1970s (Apple 1969; Kirch 1985:175; Greene 1993:191–300; Carson 2004, 2005). Puʻukoholā Heiau is an ideal structure for the application of laser scanning and 3-D modeling, as the heiau is an important cultural and historic monument that should not be disturbed or destroyed by excavation. Our model of the heiau allows us to assess the accuracy of previous mapping of the structure, provide a firm basis for future management and preservation, and enable us to estimate the volume and labor costs of its construction.

PUʻUKOHOLĀ HEIAU

The heiau of Puʻukoholā (literally meaning *the hill of the whale*) is situated on a coastal hilltop in the *ahupua*ʻ*a* of Kawaihae, located in the district of South Kohala, Hawaiʻi Island. The temple provides a unique case study because it was built after European contact in A.D. 1790 to 1791 by Kamehameha I. Puʻukoholā Heiau was the last luakini heiau built in the archipelago. There are numerous accounts of its construction and use in historical context, and it is an important structure in terms of current Hawaiian religious practice (see Greene 1993:303–338; Desha 2000; Carson 2004, 2005).

Previous archaeological studies at Puʻukoholā Heiau began with the mapping of the heiau in the 19^{th} and early 20^{th} century by Lyons in 1853, Alexander in 1869, and Stokes in 1909 (Stokes 1991:164–169). The most complete analyses to date were those presented by Kikuchi and Cluff (1969), who conducted a manual survey of architectural components and cross sections. Also, Ladd (1986) undertook a stabilization project for the National Park Service. Aside from these two studies, archaeological work at Puʻukoholā Heiau has been limited.

THE 3-DIMENSIONAL ANALYSIS OF PUʻUKOHOLĀ HEIAU

Using a 3-D laser scanner to construct a 3-D model of Puʻukoholā Heiau is a non-destructive means of examining the structure. The survey of Puʻukoholā Heiau was undertaken using a Cyrax 2500 laser scanner over seven days in July 2003. This scanner has a vertical and horizontal scan density of 0.25 mm at a range of 50 m with a distance accuracy of $\pm$ 4 mm and a positional accuracy of $\pm$ 6 mm, which makes it a useful surveying tool for complex large-scale structures like Puʻukoholā Heiau. Data from each scan is represented by a point cloud (Figure 1). The point cloud consists of four dimensions of data, including three spatial coordinates (x, y, and z) and a reflectance strength value (RSV) that represents the amplitude of laser reflectance from the target to the scanner (Allen et al. 2003). These data are visually represented as a series of points whose 3-D locations are collected by the scanner and displayed.

Surveying the heiau consisted of scanning from different vantage points around the perimeter and atop the structure to achieve a complete surface coverage. Progressive scans were registered using the

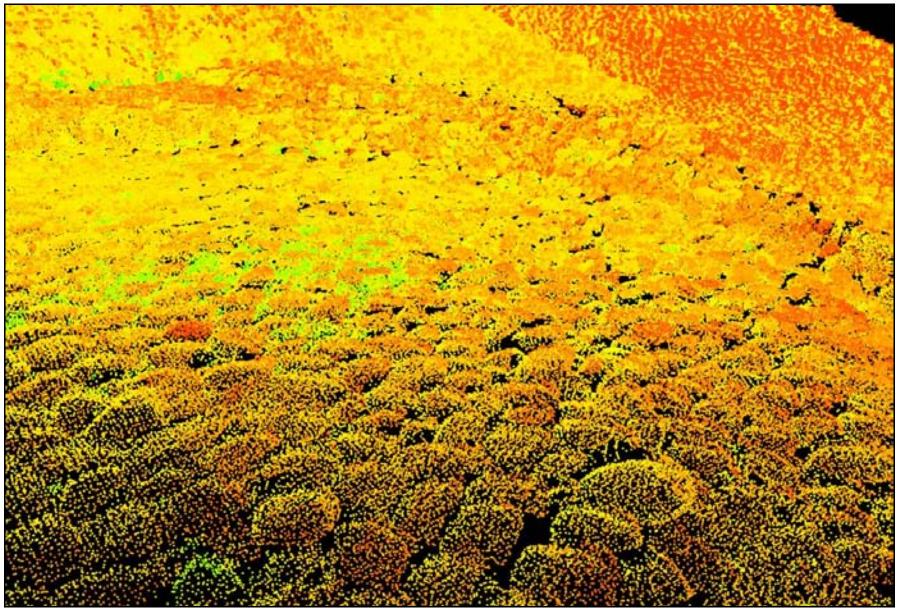

Figure 1: Close-up view of a global point cloud of an ‘āla paving.

proprietary Cyclone V5.1 software with registration targets tied to the Universal Transverse Mercator (UTM) grid system. The 3-D model was made from 76 individual scans that comprised over 40 million points with an overall RMS registration error of +/- 8mm. The global point cloud data were interpolated using Farfield Technology’s SilverLining^{TM} software. This software uses radial basis functions (RBFs) to interpolate and model irregular, non-uniformly shaped data. The resultant 3-D surface (Figure 2) was analyzed using Microstation v8 software.

Using the 3-D data, a plan view of the heiau was produced for comparison with previous maps created with manual survey instruments. As Figure 3 shows, there is a notable difference between the laser-scanner data (shown as a series of red lines) and the manual survey maps (shown as black lines), reflecting the accuracy of scanning technology. In addition, we produced 14 section views of the heiau (Figure 4). These section views were created at the same locations as those manually mapped by Kikuchi and Cluff (1969), and we found marked differences between those obtained through the two different methods. Although some of these differences can be attributed to the reconstruction of various portions of the heiau by Ladd in 1986, many of the differences can be attributed to the inaccuracy of hand-drawn, manual instrument maps.

Another useful feature of these section views is that they can be used to isolate and examine the relationship between different structural components of the overall structure of Pu‘ukoholā Heiau. As shown in Figures 5 and 6, the structure is composed of a variety of components that reflect its complex nature. Five types of structural components were isolated and identified. These include walls, terraces,

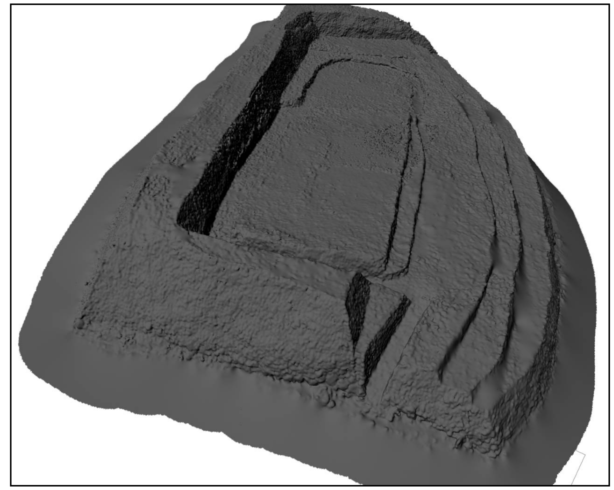

Figure 2: Three-dimensional model of Pu‘ukohola Heiau looking south-southeast.

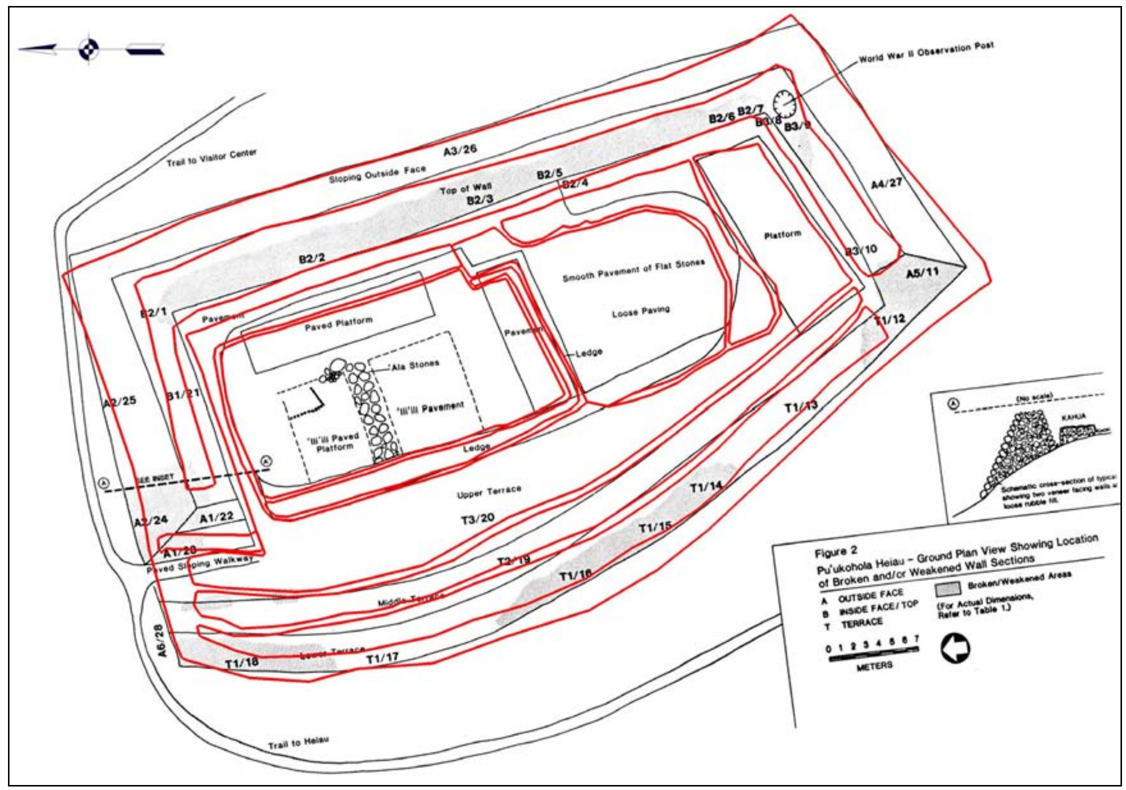

Figure 3: An overlay of the 3-D laser scanner data and a map made by Ladd (1986).

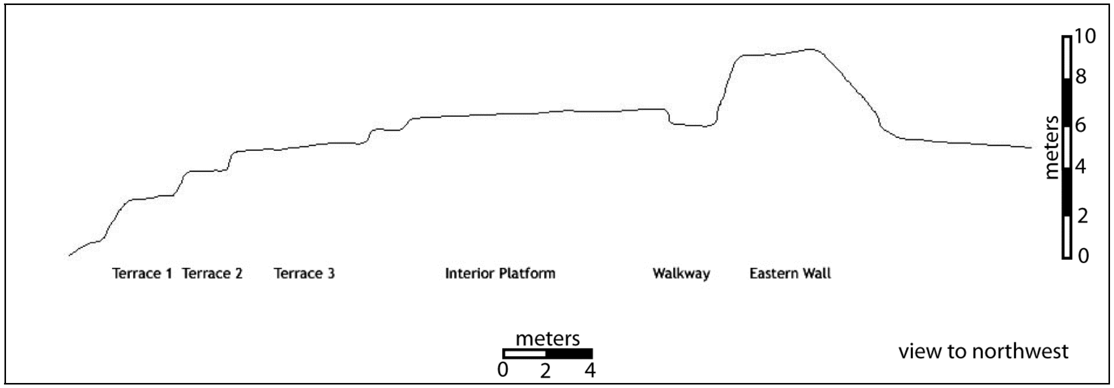

Figure 4: A section view of the heiau generated from the 3-D data.

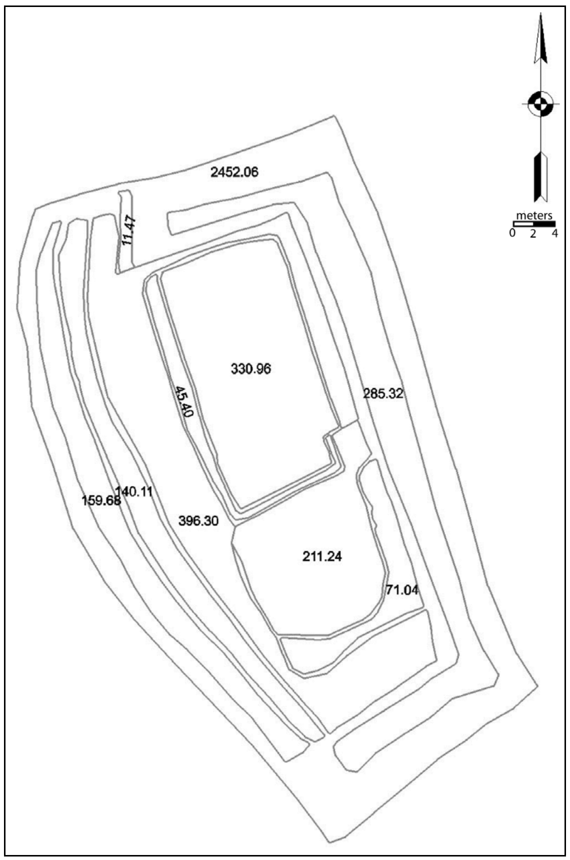

Figure 5: The individual components of the heiau identified in the 3-D data with surface areas indicated.

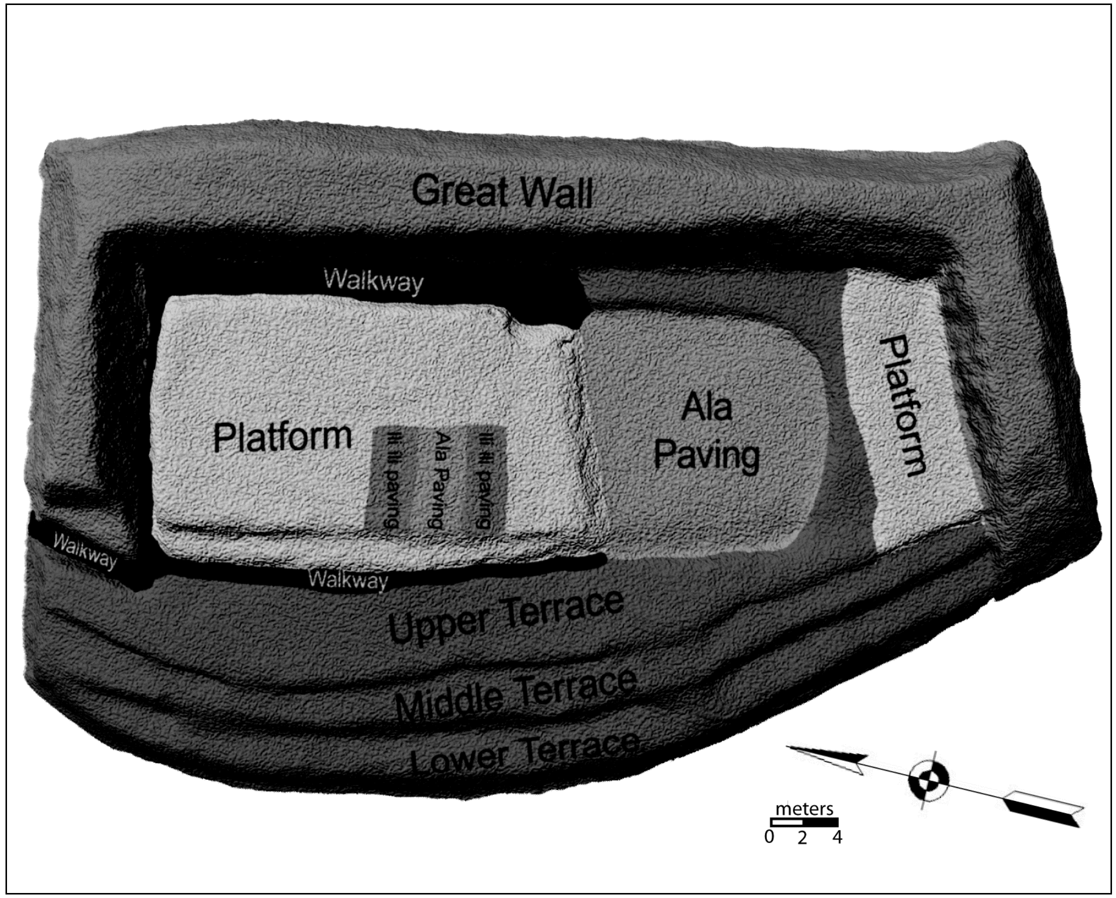

Figure 6: A plan view of the 3-D model showing different structural components.

pavings, walkways, and platforms (Table 1). The creation of the section views from the scanner data enabled the clear identification of these components, which facilitated further volumetric analysis.

To extract volume, the model was placed into Microstation v8, and the natural underlying outcrop (which is visible in places on the surface) was used to extrapolate the base of the heiau without excavation. Next, the surface areas of each structural component that had been isolated with the acquisition of the section view data were calculated. The final step was the calculation of volume based on the constructed underlying topography. Pavings were assigned a maximal depth of 30 cm, which was based on Kolb's (1991) data from excavated structures in Maui. Using these assumptions, the overall volume of the structure was estimated to be approximately 5,306 cubic meters.

We used the volumetric data to calculate the number of days it would have taken to build the heiau. Our methodology is based on Kolb's (1991) labor estimates for Maui heiau, which in turn had

Table 1: Architectural components of Puʻukoholā Heiau.

Component	Area (m^2)	Volume (m^3)	Specific gravity	Weight (kg)	Transportation rate (kg/worker/day)	Transportation cost (days)	Construction rate (kg/worker/day)	Construction cost (days)	Total cost (days)
Walls	2,024	1,707	2,930	5,002,799	1,000	5,003	2,500	2,001	7,004
High terraces	707	2,635	2,930	7,721,019	1,000	7,721	2,500	3,088	10,809
Low platforms	437	455	2,930	1,333,033	1,000	1,333	5,000	267	1,600
ʻIliʻili pavings	85	25	2,930	74,686	500	149	5,000	15	164
ʻĀla pavings	184	55	2,930	161,355	500	323	5,000	32	355
Paved walkways	171	146	2,930	426,549	500	853	5,000	85	938
TOTAL	3,608	5,023	NA	14,719,441	NA	15,382	NA	5,488	**20,870**

followed the work by Erasmus (1965) from the Maya region. Different components (i.e., pavings, terraces, platforms, and walls) incurred varied transportation and construction costs in terms of labor. The total labor necessary to construct Pu‘ukoholā Heiau was determined by calculating the transportation and construction costs of the individual components and then adding those figures together.

One consideration that must be taken into account is the variable cost of obtaining and transporting different types of building material. Three types of material were used to construct Pu‘ukoholā Heiau: 1.) rough basalt boulders from the surrounding outcrops, 2.) ‘*ili*‘*ili* (water-worn pebbles), and 3.) ‘*āla* (water-worn beach cobbles). The latter two types of rock are not as widespread as the basalt fill that comprises the majority of the structure—the closest source of ‘āla and ‘ili‘ili at the coast is approximately 200 m away. Furthermore, ‘ili‘ili would have required substantially more effort to collect than rough basalt because they would have required collection and transportation in a container of some sort. Based on these considerations and the assumptions used by Kolb (1991:133–136), we estimate that a worker could collect and transport 1,000 kg of basalt per day, compared to 500 kg of ‘āla and ‘ili‘ili. Although these estimates are gross assumptions at best, they have been derived from reasonable experiments, and they are the best estimates available for the basis of our calculations.

Construction costs were calculated based on Kolb’s (1991) review of experimental data. Kolb (1991) found that different types of structural components required different amounts of labor to construct, and therefore it is important to differentiate the rate or amount of labor necessary to build each component. For example, it would be easier and faster to build low platforms than it would be to build high platforms or walls. We used Kolb’s (1991:138) rates of construction and assumed that a worker in one day could build 5,000 kg of a low platform, terrace, or ‘āla or ‘ili‘ili paving, but only 2,500 kg of a high terrace or wall.

To calculate the number of labor days it took to construct Pu‘ukoholā Heiau, we took the volume estimates of the individual structural components provided by the 3-D model and estimated the weight of each of these components by simply multiplying the volume by a specific gravity of 2,930 kg/m^3. This value is derived from Kolb (1991:132) who cites a specific gravity value for basalt of 2.93 gm/cm^3 (a figure taken from Dana 1878:451). Although specific gravity varies greatly based on the density of different types of basalt, this average figure was used in order to be consistent with Kolb’s estimates from Maui heiau. Once we had the weight of the individual components, we could establish the transportation cost of the component by dividing by the appropriate transportation rate constant. The total amount of labor days for that component was simply the sum of the transportation and constructions costs. The total labor costs of the individual components of Pu‘ukoholā Heiau are shown in Table 1. The sum of the individual components is the total amount of labor needed to construct the heiau.

The above data suggest approximately 20,870 labor days to build Pu‘ukoholā Heiau. Ethnographic accounts state that the heiau was built over a one-year period, with a two-month break from March to May, thus indicating 296 days devoted to construction. The total estimated labor days (20,870) can be divided by 296 to conclude that the total construction labor entailed approximately 71 workers for each of the 296 days.

Our estimates are not without limitations. We extrapolated the depth of the underlying substrate of the heiau based on the surface visibility of outcrops, and this estimate cannot be verified except by extensive excavation. Furthermore, the isolation of various structural components by digital means was not 100 percent accurate in assessing the overall volume of the structure. When summed, the individual volume measurements added to 5,024 m^3. This measurement differs slightly from the overall calculation of 5,306 m^3 for the entire structure. This discrepancy is representative of the inherent difficulty of isolating the subsurface portions of structural features when confined to surface observations.

As with any study that relies on experimental archaeology for quantitative figures, this study may be inherently flawed by the use of Erasmus' (1965) data from the Maya region. By taking experimental estimates from one geographical region to another, there are bound to be quantitative and qualitative differences. Different transportation and construction techniques may have produced different labor costs, resulting in a different overall estimate for labor days required to construct the heiau. For example, it is assumed that the Hawaiian method of passing rocks hand-to-hand in a human chain will produce comparable results to the transportation by a single laborer over a set distance (Kolb 1991:134). Without experimental work that is specific to the methods employed by Hawaiian laborers, there is no way of quantifying this assumption. Furthermore, it is impossible to determine the sources of rocks without geological sourcing, and the distance estimates employed may be flawed as a result.

The experimentally derived data are especially problematic in the case of Puʻukoholā Heiau because there is some discrepancy in the literature regarding the source of the rocks used to build the heiau. There is a popular belief that the rocks used to build the heiau were passed hand-to-hand from Pololū Valley some 22.4 km distant. However, according to Thrum (1907:60), this belief may actually be the result of a misunderstanding because it refers to Moʻokini Heiau in North Kohala, which was also an important heiau used by Kamehameha. Fornander (1918–1919 2:328) states that a local informant from Kawaihae who assisted in the building of the Puʻukoholā Heiau described its construction as being completed by thousands of people encamped on the surrounding hillsides of the structure. From this account, we may assume that these laborers were working in the local vicinity to build the heiau from local materials.

Within the constraints of those limitations, our estimate of 71 people working for ten months to construct Puʻukoholā Heiau might seem low when considered in terms of total demographic estimates for the region. It is, however, still a significant number of people who would have required economic support in exchange for their labor. The staple finance needed to support such an endeavor would have been substantial, showing that centralized control over economic production was in place. The political power displayed in the commission of a large luakini heiau and the associated ideological significance of such a structure would have had important implications for the people of the highly stratified Hawaiian society. The religious role of the sacrificial temple is underlain with notions of political power and authority. The layout of the temple prohibits proceedings inside the heiau from being viewed from any sides except for the *makai* (seaward) side. This made a clear distinction between the elite who would have been allowed to enter the sacred space and the commoners who were not. Its location on a hilltop makes it clearly visible from the surrounding landscape and allows the imposing structure to be viewed as a material manifestation of power. The building of such a monument clearly displays the economic, political, and ideological power of the *ali'i nui* (paramount chief). A massive structure of this kind therefore provides a permanent symbol of chiefly power and authority.

CONCLUSION

Three-dimension laser scanning enhances our understanding of the construction and form of heiau. The extraction of section views and volumetric data without the need for archaeological excavation is an effective and non-destructive technique. Heiau are visible manifestations that reflect the indigenous Hawaiian social, political, and ideological structure, and they are integral to our understanding of Hawaiian culture. By creating 3-D models of these monuments, we can record their current condition and monitor their preservation. We can also make accurate estimates of their volume, which can be used to estimate construction costs. As the rate of destruction of archaeological sites continues to climb, these digitized models will be essential for future archaeological studies. The scanning and modeling of Pu'ukoholā Heiau provides the first step in implementing such an approach.

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