The colossal hats (pukao) of monumental statues on Rapa Nui (Easter Island, Chile): Analyses of pukao variability, transport, and emplacement

Sean W. Hixon*, Carl P. Lipo, Ben McMorrann, Terry L. Hunt

Department of Anthropology, 403 Carpenter Building, Pennsylvania State University, University Park, PA, 16802, USA
b Department of Anthropology, Binghamton University, Binghamton, NY, 13902, USA
c Department of Physics, University of Oregon, Eugene, OR, 97403, USA
d The Honors College and School of Anthropology, University of Arizona, Tucson, AZ, 85721, USA

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ABSTRACT
The archaeological record of Rapa Nui (Easter Island, Chile) is noteworthy for its massive statues (moai) that were transported over long distances with relatively small numbers of people and minimal use of resources. Equally impressive are the colossal bodies of red scoria (pukao) placed on the heads of many of the moai. In this study, we use three-dimensional models of 50 pukao found across the island and 13 red scoria cylinders from Puna Pau, the island's pukao quarry, to study the process of pukao manufacture, transport, and placement atop statues. Our analysis identifies surface features that are explained by the process of construction and transport of these multi-ton objects. Based on shared physical features of pukao, evidence in the archaeological record, and the physics necessary for pukao movement, we propose a falsifiable hypothesis in which relatively small numbers of people rolled pukao up stone ramps to place pukao atop moai. We conclude that activities of pukao production and transport did not require oversight by a centralized political authority, nor do they support notions of a large population that collapsed with “ecological suicide” on Rapa Nui.

1. Introduction

The archaeological record of Rapa Nui (Easter Island, Chile) is well-known for its monumental architecture and massive stone statues (moai) that were transported across miles of rugged terrain. Beginning with Polynesian colonization of the island in the 13th century AD (Hunt and Lipo, 2006), prehistoric people made nearly 1000 moai and transported hundreds, including some measuring about 10 m tall and weighing up to 74 metric tons. As part of the process of making the moai, these massive statues were “walked” along prepared roads to reach constructed stone platforms known as ahu (Lipo and Hunt, 2005; Lipo et al., 2013). While the ingenuity and effort involved in moving the moai makes these monuments among the most impressive examples of prehistoric engineering, the people of Rapa Nui did even more. In many cases, once the moai reached their ahu locations, the Rapanui added massive red scoria cylinders (pukao) atop the moai. Pukao originate from a quarry known as Puna Pau, and prehistoric islanders transported over 50 of these giant masses across the island, as far as 13 km distant (Fig. 1). The largest of the pukao (located at Te Pito Kura on the north coast) is over two meters in diameter, weighs nearly 12 metric tons, and was moved over 12 km.

The prehistoric achievements of Rapa Nui are especially notable given the island’s diminutive size, remoteness, and lack of natural resources. Nearly 2000 km (1200 miles) distant from the nearest inhabited land, the island is just 163.6 km² (63.2 square miles). Formed from three now-extinct volcanoes (Bandy, 1937), the island’s soils are nutrient poor and excessively drained, thus resulting in low plant productivity and limited surface water sources (Bandy, 1937; Herrera and Custodio, 2008). The contrast between the spectacular nature of the archaeological record and the island’s lack of natural resources has led some to argue that the moai were part of an irrational cult that led to overpopulation and an overexploitation of resources, ultimately resulting in prehistoric “ecocide” (Bahn and Flenley, 1992; Diamond, 2005).

Recent research, however, has called into question long-standing claims for “ecocide” and population collapse before European contact (Hunt and Lipo 2009, 2011, 2012; Mulrooney et al., 2009). For example, the cumulative impacts of fire and rat predation on seeds of native plants played a significant role in deforestation (Hunt, 2007), and agricultural productivity was always limited by nutrient poor soils (Ladefoged et al., 2005). It is doubtful that the prehistoric population ever exceeded much more than around 3,000, as estimated by early
European visitors (Hunt and Lipo, 2011). While some historic observations note that islanders were relatively unhealthy and struggling to survive (Ruiz-Tagle, 2005), old-world diseases and slave-trading account for drastically reducing the island’s population in the 18th and 19th centuries (Fischer, 2005; Richards, 2008).

There has been abundant experimental work about the possible ways in which moai and pukao were transported (e.g. Heyerdahl and Ferdon, 1961; Pavel, 1995; Van Tilburg and Ralston, 1999; 2005). These inquiries, however, have tended to focus on exploring plausible solutions rather than constructing falsifiable explanations of the archaeological record, leading to continued speculation. In contrast, constructing explanations for transport requires us to identify pukao features that can only be explained by one mode of transport or another. By focusing on sufficient and necessary attributes combined with models based in physics, we can then deduce the most parsimonious explanation: one that necessarily accounts for the observed attributes and configuration of the archaeological record.

We have begun to accomplish this task for moai. In a recent study of the variable form of moai in the archaeological record, Lipo et al. (2013) demonstrated that the features of moai found along the prehistoric moai roads, the positions of statues along ancient roads, and patterns of statue breakage can be explained only if the statues were in a standing position prior to falling. They also showed how the remarkable forward lean for unfinished moai found on roads prohibits these statues from standing at ahu but enables “walking” moai in a vertical position. Finally, Lipo et al. (2013) empirically demonstrated that relatively small groups of people could move even the largest statues without timber and with only rope. In light of new information about the island related to the low-density and dispersed settlement pattern (Morrison, 2012), the nutrient-poor soils (Ladefoged et al., 2005), the effects of rat predation on native palm forests (e.g., Hunt, 2007), and the lack of evidence for a prehistoric collapse (e.g., Hunt and Lipo, 2012), this detailed understanding of moai transport supports the emerging understanding for the island that challenges any direct link between the statue building and deforestation of Rapa Nui.

This study of pukao, therefore, takes a similar approach. We examine the physical features of pukao in light of the physics of transport in order to develop hypotheses for pukao transport that are based directly on evidence in the archaeological record. In this way, we can move beyond merely speculative or plausible reconstructions.

2. Background and approach

While the first European visitor to Rapa Nui, Jacob Roggeveen, noted the presence of “baskets” on top of the moai in 1722 (Ruiz-Tagle, 2005:32), the members of the Spanish expedition to Rapa Nui in 1770 were the first to describe the scoria cylinders atop moai in any detail. F. A. de Agüera y Infanzon (Corney et al., 1908:95) notes, “the diameter of the crown is much greater than that of the head on which it rests, and its lower edge projects greatly beyond the forehead of the figure; a position which excites wonder that it does not fall.” Early European visitors recorded through descriptions and illustrations that pukao generally consist of a cylindrical body with an oblong cross section and a top cylinder of smaller minimum and maximum diameters (Fig. 2, Kahn, 1968; Ruiz-Tagle, 2005).

Serious speculation as to the meaning of the scoria cylinders atop moai began in the early twentieth-century with the visit of Katherine and Scoresby Routledge in 1914–15. Scoresby Routledge (1917:334), followed by Rivers (1920) and Skinner (1922), advanced the notion...
that pukao represented a “hat” by noting a parallel between the shapes of pukao and “a hat very commonly worn made of native grass” that is “not dissimilar to that of the images.” In contrast, Balfour (1921:71) argued that the scoria bodies are imitations of hair. Based on a hairstyle popular among the Rapanui, Métraux (1971:301) introduced the name “pukao” when referring to the scoria cylinders atop moai, and this name is now most commonly used for these features.

Beginning with Cook’s account (Ruiz-Tagle, 2005:163), historical sources conclude that the Rapanui transported red scoria bodies from Puna Pau to many points around the island by rolling them as large cylindrical bodies (Fig. 3, Heyerdahl and Ferdon, 1961:373; Mulloy, 1970:17; Routledge, 1998:199). At the Puna Pau source quarry, numerous large cylindrical bodies can be seen that were excavated from the volcanic crater (Hamilton, 2013). We know that the islanders used this cylindrical form to facilitate transport of the pukao between the quarry andahu destinations based on an example found near Anakena on the north shore of the island (Fig. 3). Here, a massive red scoria body sits a few hundred meters from Ahu Nau Nau and Ahu Ature Huke along what may be a prehistoric road feature. This large cylinder appears to represent a pukao “pre-form” abandoned during transport. The upright “wheel” position and wear of the cylinder is consistent with transport by rolling: a process which required the least cost and effort.

2.1. Positioning pukao on moai

While the means by which pukao were transported across the island is relatively unambiguous, researchers and visitors have long speculated on how the prehistoric Rapanui placed pukao atop moai (Altman and Morin, 2004; Lee, 2012; Mulloy, 1970; Routledge, 1998; Ruiz-Tagle, 2005; Thomson, 1891). Pavel (1995:71) first demonstrated that a 900 kg replica pukao could be slid up a height of three meters along an incline consisting of two spruce logs. In 1998, Van Tilburg raised a 680 kg replica pukao along with a nine metric ton replica moai (Van Tilburg and Ralston, 2005). In her demonstration, Van Tilburg used wooden beams to lash the pukao and head of the moai together while the statue lay in a horizontal position. She then raised the moai and pukao together by building a wedge of stone rubble beneath them and leveraging the statue upright.

Despite these attempts to explore some possibilities for pukao transport, no published research systematically examines the archaeological record for empirical evidence related to pukao transport and placement. To accomplish this task, a number of assumptions must be made. First, the quality of stonework found across the island demonstrates that the prehistoric Rapanui were capable of finely crafting figures, blocks and shapes of nearly any sort from volcanic bedrock. Thus, as with the moai, the biggest challenge that islanders faced was carving features that could be transported from the quarry to the ahu locations. Second, like moai, we expect that part of the shapes of pukao will reflect the physical constraints associated with transport and that different transport methods constrain aspects of pukao variability in different ways. Pukao variation not constrained by function for transport is free to vary to a degree driven by the effects of drift among local traditions (i.e., are stylistic, sensu Dunnell, 1978). In contrast, those details of pukao variation affecting transport performance are more strongly constrained and thus under selection (i.e., functional traits, sensu Dunnell, 1978; see also Lipo et al., 2012). In the case of moai, for example, the observation of the consistent forward-lean of road moai (i.e., those abandoned in transport) led to the recognition that the forward-falling position is a significant functional detail related to transport (Lipo et al., 2013). Similar recognition of functional and stylistic aspects of pukao variability can shed light on pukao transport.

2.2. Data generation

Shared attributes related to pukao transport may take a variety of forms. For example, shape and symmetry affect a pukao’s balance, grooves along a pukao surface may indicate wear, and notches may indicate points of contact between the pukao and other surfaces. To systematically examine variability in pukao form, we used structure-from-motion (SfM) mapping to generate detailed three-dimensional models of pukao surfaces (Hixon et al., 2018). During our 2014 field season, we generated a total of 15,000 overlapping photographs for 53 of the 75 pukao and 13 of the 23 Puna Pau scoria bodies mapped during survey work conducted by Hunt and Lipo (Hochstetter et al., 2011). Using these photographs and the software AgiSoft Photoscan (2011), we produced three dimensional models of pukao. Each model was cleaned and trimmed to remove extraneous features using Meshlab: an editing system for managing three-dimensional meshes (Cignoni et al., 2008). We then extracted metric data from models and calibrated these data with field measurements. Finally, we used Meshlab to extract a variety of physical dimensions and surface attributes.

3. Results

Our analysis of pukao form and surface detail focused on 50 coastal pukao and 13 of the cylindrical red scoria bodies at the Puna Pau quarry. Beyond a generally cylindrical form topped by a cylinder of smaller diameter, few attributes of pukao form are shared throughout the island. There also exists significant variation in pukao surface details, but carved base indentations exist on all observed coastal pukao. These base indentations constrain possible modes of pukao transport.

3.1. Pukao form

Pukao are cylindrical bodies with an oval cross section. Four pukao slightly taper upwards, but one at Anakena significantly tapers to approximately 60% of base diameter to create a truncated conical form (Fig. 4). Since conical forms are difficult to roll from the quarry, it is likely that the Rapanui completed at least some pukao only after placing the pukao atop moai. This idea is supported by evidence of red-scoria debris found in ahu deposits during excavation (Sergio Rapu, personal communication) and the smaller sizes of finished pukao relative to the massive unfinished bodies found at Puna Pau and near Anakena.

Pukao form can be characterized by two ratios that describe the proportions of a cylinder with an oval section. The first ratio consists of the minimum diameter divided by the maximum diameter and characterizes the degree to which the oval cross section is oblong. The second ratio, minimum diameter over height, describes how squat the pukao is. Note that all but two pukao (both at Anakena) that appear relatively complete are topped with an attached cylinder of smaller diameter (Fig. 4). We characterized the form of these smaller top cylinders using the aforementioned two ratios. Fig. 5 shows trends in
these aspects of pukao variability by island region. Sector I includes the pukao on the SW coast, Sector II consists of those on the SE coast, and Sector III covers those on the NE coast.

The variability in pukao form suggests that few attributes beyond a relatively round cross section were constrained by transport. For example, the carved top cylinders display a high degree of variability throughout the island, with significant differences between the northern and southern coasts (Fig. 5). The spatial patterning in pukao form also supports the hypothesis that shape differences are largely stylistic and reflect traditions of carving rather than technological constraints. Spatially structured variation in pukao form matches patterns in other artifact classes (e.g., obsidian stemmed tools, mata’a, Lipo et al., 2016), skeletal variability (Furgeson and Gill, 2016; Gill, 2016), and ancient DNA (Dudgeon et al., 2016), all of which support the idea that populations across the island interacted largely as small, functionally redundant, hyper-localized communities (see also Morrison, 2012).

3.2. Pukao surface variation

From our analysis of three-dimensional models, it is clear that the vertical surfaces of pukao hold a variety of linear and curvilinear indentations, some of which may be interpreted as petroglyphs (Hixon et al., 2018). Of 50 coastal pukao, 27 (54%) include at least one petroglyph, and 12 of the 13 (92%) large scoria bodies at Puna Pau are adorned with petroglyphs. These decorations are unlikely to have been related to the technology of transport and may have been added either after the pukao reached the top of the moai or after pukao fell to the ground.

The undersides of bases of pukao (Fig. 6), however, have a feature that is widespread and most clearly associated with pukao emplacement atop moai. Specifically, well-preserved pukao with bases exposed (n = 10) all possess bases with large shallow indentations that would have fit the shape of the top of the moai head and were previously observed by past European visitors to the island (Heyerdahl and Ferdon, 1961:372; Ruiz-Tagle, 2005:58). Often, the back edge of the base indentation is more deeply carved than the front edge. This indentation could not have been carved after the pukao was placed atop

![Fig. 4. Variability in pukao form. The conical pukao 65 at Anakena (left) contrasts with the cylindrical pukao 49 at Tongariki (middle) and pukao 18 at Vaihu (right). Note the differences in top cylinder form between pukao 49 at 18.](image)

![Fig. 5. Spatial comparison of pukao body and top cylinder mean dimensions by sector with shape aids for visualization. Sector I locations constitute those pukao found on SW coast (n = 30), Sector II are those found on the SE coast (n = 10), and Sector III comprises all pukao on the NE coast (n = 10). Statistical significance is indicated by * (p < 0.05), ** (p < 0.01), *** (p < 0.001) and “ns” (p > 0.05). Note the dramatically more elongated top cylinders observed in Sector III.](image)
the moai, and the indentation is not necessary to stabilize the pukao on an upright moai due to the fact that the downward projection of the pukao center of mass falls within the flat area of contact between the pukao and moai. Significantly, these base indentations would have made positioning pukao on the statues by sliding more difficult. The poor condition and concealed bases of most of the 50 coastal pukao make it difficult to observe many base indentations, but this widespread surface feature has implications for pukao and moai placement, which we discuss below.

4. Moai and pukao transport

Given that our goal is to describe and explain the archaeological record, our explanation of moai and pukao transport derives directly from the observed attributes of these artifacts. Ultimately, we pose transport hypotheses that are not only feasible but, just as with moai transport, are consistent with explaining the evidence of the archaeological record. Where cost is a consideration for performance, repetitive tasks will generally converge on least or relatively low cost solutions, mediated by innovation, social learning, and trial-and-error. Such evolutionary processes do not guarantee lowest cost solutions, but they generally lead to strong winnowing, particularly when costs and consequences are high.

Based on our knowledge of how moai were “walked” to the platforms using the effects of a forward lean and a rocking motion (Lipo et al., 2013), once moai reached their destinations, islanders then faced the challenge of modifying the base to stand the moai stably upright. This step transforms the statue from one that had a 10–35° forward lean to one with the center of mass well over the base. At the same time, islanders would have begun to consider the process of placing the pukao atop some of the statues. We hypothesize that these two tasks were accomplished simultaneously. Based on the amount of rocky material that forms the “wings” of many ahu, it is has long been argued (e.g., Thomson, 1891:449) that the Rapanui constructed some kind of rubble-filled ramp to help raise the moai and pukao and that they then repurposed the ramp material in wing construction. Given that seawalls of ahu often drop precipitously to the intertidal zone and that moai are aligned along the length of ahu parallel to the coastline, it is feasible to construct a ramp for pukao transport on only the interior side of the ahu.

Building a ramp in front of the forward-leaning (as opposed to upright) moai serves three purposes. First, the moai’s forward lean would slightly reduce the required height and length of a ramp. Second, the lean serves to prevent the moai from toppling or sliding backwards with the weight of the ramp. Note that ramp material in contact with the moai may be relatively consolidated to diminish the force that the ramp exerts on the retaining moai. Finally, the lean aids the placement of the pukao on top of the moai once the former reaches the top of the ramp.

Ramp material, which can be used to help walk the moai up a small height to the top of the ahu, can include stone and soil. The pukao preform is then rolled up the ramp. Of course, rolling a multi-ton cylinder up a ramp is a non-trivial task. This work can be eased substantially by using a parbuckle strategy, and our models and calculations show that 15 or fewer individuals are capable of parbuckling any observed pukao up a ramp of reasonable size. In a parbuckle setup, one passes a doubled rope around a cylindrical object on its side, anchors one end of the doubled rope at a point up-ramp of the object and pulls on the other end of the doubled rope (Fig. 7). Stakes at the top of the ramp or the top of the moai can serve as the anchor in the parbuckle setup, and breaks, steps, or stone props in the ramp may ease this stage of transport. Historically, parbuckling was a common technique for moving cylindrical objects (e.g., barrels) up and down ramps (Cotterell and Kamminga, 1992), and the same mechanical advantage is used to right sunken marine vessels during salvage. For example, the 1943 salvage of USS Oklahoma during the Second World War involved parbuckling (Morris, 1947). Though parbuckling enables more workers to participate in transport, groups of two or three people down slope of the pukao can aid by levering.

The only resources required to make the parbuckle system work are stout rope and possibly small wooden levers. The same requirement would have been the case for moai transport (Lipo et al., 2013). Rope was certainly available to the Rapanui, and ethnohistoric accounts document the local tradition of producing cordage and rope made from hau hau (Triumfetta semiretiloba), which is a woody shrub that still grows on the island (Métraux, 1971:210). The wooden lever that may have assisted moving the pukao from below requires only relatively small branches from trees found on the island (e.g, Sophora toromiro, Horrocks et al., 2012).

Parbuckling a pukao up a ramp has significant advantages over sliding and better explains the archaeological record. First, a mechanical advantage associated with parbuckling decreases by half the force required to move a pukao up an incline. Second, rolling by parbucking takes advantage of the force of friction between the pukao and ground instead of fighting this force. The absence of evidence for sliding on pukao bases (including the presence of base indentations) and lack of wear from friction support the conclusion of rolling by parbuckling.

Transport equations based on Newtonian physics (Equations S12 and S14, see derivations in Supplementary Material), human strength estimates (Snook and Ciriello, 1991), and estimates of moai height and pukao mass at four different ahu (Table 1) verify that pukao transport by rolling up a ramp is physically feasible with 15 or fewer people, even in the case of the most massive pukao (about 12 metric tons) at Te Pito Kura. Graphing the force required to pull or lever pukao up a ramp with a given angle of incline at each location (i.e., combining Equations S12 and S14 with the values in Table 1) produces Fig. 8. Basic human strength estimates (Snook and Ciriello, 1991), support the conclusion that relatively small numbers of people can transport a pukao up a ramp with angles of incline between 5° and 20°. Though conservative, since these modern workforce strength estimates are intended to prevent
Table 1
Estimated dimensions of pukao, moai, and ahu at four locations used in sample physical calculations graphs. True to the equations derived in the Supplementary Material, \( h \) denotes the combined height of the erect moai and ahu over the surrounding ground, \( m \) denotes the mass of the pukao, \( R \) denotes the radius of the pukao, and \( k \) denotes the estimated lever arm associated with pushing. An estimate of 2.0 m for \( k \) is reasonable when assuming shallow lever angles and that human height ranges between 1.5 and 1.6 m. Measurements from Te Pito Kura are taken from Heyerdahl and Ferdon (1961). Other measurements are taken from the field and from models generated in this project. Note that pukao mass estimates are based on the assumption that scoria has a density of 1550 kg/m\(^3\) (Edwards et al., 1996).

<table>
<thead>
<tr>
<th>Number</th>
<th>Area (m(^2))</th>
<th>Thickness (m)</th>
<th>Volume (m(^3))</th>
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</thead>
<tbody>
<tr>
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<td>1440</td>
<td>1.5</td>
<td>2160</td>
</tr>
<tr>
<td>Ura Uranga te Mahina</td>
<td>900</td>
<td>1.5</td>
<td>1350</td>
</tr>
<tr>
<td>Akahanga</td>
<td>1360</td>
<td>1.5</td>
<td>2040</td>
</tr>
<tr>
<td>Te Pito Kura</td>
<td>1020</td>
<td>1.5</td>
<td>1530</td>
</tr>
</tbody>
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Fig. 8. Applied force required to move pukao up ramps with variable angles of incline at four different numbered ahu (1 = Te Pito Kura, 2 = Vaihu, 3 = Akahanga, and 4 = Ura Uranga te Mahina). Solid black lines represent force required with only pulling, and dashed lines represent force required with only pushing. When we consider a human strength estimate of 70 kg (686 N) per person, we can draw the three horizontal red lines, which approximate the forces that can be applied by 5, 10, and 15 individuals. The largest pukao (1, that at Te Pito Kura) requires the longest ramp for any given applied force, followed by that at Vaihu (2), Akahanga (3), and Ura Uranga te Mahina (4). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.1. Ramp considerations

William Mulloy acknowledges the possibility of such transport but objects that ramps (specifically at Te Pito Kura) would need to be “several hundred meters long – a seemingly prohibitive amount of construction” (1970, 15). However, ramps several hundred meters long would not have been needed at any locations analyzed when we plot force required to move a pukao using parbuckling techniques against the length of the ramp (Fig. 9). In Fig. 9, the x-coordinate of the intersection of the red and black lines give estimates of ramp lengths possible with different numbers of people at different locations. Even at Te Pito Kura (1), where the largest known pukao was placed atop the tallest transported moai, just ten people pulling the pukao can do so with a ramp length of less than one hundred meters. At Vaihu (2), groups ranging in size between just ten and fifteen individuals are capable of pulling the pukao up a ramp with a length between about 23 and 32 m.

In support of the long-held speculations for past re-purposing of ramps in ahu wings, the volumes of ramps required for such transport coincide with (i.e., are less than or equal to) the estimated volume of the ahu wings at each of the four locations (Table 2). We use Equation S24 to calculate the volume of ramps. In this calculation, we assume that the path width of the ramp is the height of the pukao plus a margin of 60 cm on either side. Additionally, we follow Mulloy’s (1970:16) idea that the sides of the ramp taper away from the central path at an angle between small lever movements is great.
of 60° from horizontal.

Ahu Vaihu provides an example. With ten people successfully pulling (Fig. 10), an angle of incline of about 13° or less is required (Fig. 8). Based on Equation S(24), the volume of such a ramp would be approximately 730 m$^3$, which is well below the approximate ahu volume of 2160 m$^3$ (Table 2). Overall, the volume of the ramp would spread over the area of the ahu at Vaihu with a thickness of about half of a meter. For a modern analogy, this corresponds to the volume of material spread with a thickness of about 14 cm over an American football field (area of about 5351 m$^2$). In general, ramp volume estimates support Thomson’s (1891, 449) idea that “the stones which formed the foundation of the roadway were disposed of in building the wing-extensions of the platform [Fig. 11].”

While little physical evidence for ramps remains, it is likely that a spread of cobbles in front of an ahu on the southern coast (Fig. 12) constitutes the remnants of a pukao ramp. A ramp with the observed length is feasible for pukao transport. Specifically, a ramp length of about 13 m and a moai/ahu height of about 8 m would dictate a ramp angle of incline of about 32°. A ramp with these dimensions would have had a reasonable volume (less than 500 m$^3$, Equation S(24)), and about 8000 N of force would have been required to roll a pukao up the ramp through parbuckling (Equation S(14)). This configuration roughly corresponds to the pulling force of about a dozen individuals (Snook and Ciriello, 1991), so we find that it is physically feasible for the stone body in this case to represent the remnants of ramp with roughly original orientation and extent.

### 4.2. Pukao placement

Upon reaching the top of the ramp, the pukao preform would need to be prepared, positioned, and set into place. If the ramp path came directly in front of the moai, then final pukao preform placement
involves first rotating the pukao on its side 90° and then tipping the pukao so that its base comes in contact with the top of the moai. Little physical evidence related to final placement exists, especially given that the sides of at least some pukao (e.g. conical pukao in Fig. 4) were likely modified only after reaching the top of moai. The rotation of pukao could have been accomplished by excavating the ramp material beneath the preform, manipulating the preform through levering, and manipulating the preform by using rope. However, given limited space at the top of the ramp, rotating the pukao would have been a challenge. The problem of rotating the pukao could be avoided if the ramp path came to the immediate side of the moai. This scenario still involves tipping the pukao over the edge of its base. Much of the tipping could be accomplished by excavating ramp material beneath the base edge of the pukao, and a combination of levering and pulling may have assisted. Note that the presence of a top cylinder may aid the tipping of pukao given the possibility of wrapping rope around the top cylinder and pulling from behind or beside the moai.

4.3. Explaining the base indentations

The presence of base indentations on all well-preserved pukao (i.e., where bases are preserved and observable) is also well-explained by this transport model. First, if a pukao is resting on its base prior to emplacement, then it is difficult to carve a properly-oriented base indentation to match the top dimensions of a moai. To avoid this problem, following the carving of a pukao base indentation, the pukao could be flipped over and carefully rotated so that the base aligned with the shape of the top of the moai head. Second, if the shallow base indentation was made prior to sliding the pukao up the ramp (as would be necessary in the scenario suggested by Pavel [1995]), then friction between the ramp and friable red scoria of the pukao would damage or obliterate the base indentation. The lack of striations from wear along pukao bases supports the conclusion that sliding was not used to move and place pukao. Refinishing once the pukao was placed atop the moai would be unlikely to completely remove scratches that would have resulted from sliding on the base. Pukao base indentations may be consistent with the scenario in which pukao and moai are erected simultaneously (Van Tilburg and Ralston, 1999), but we consider this scenario unlikely, because 1) the base indentation is superfluous in this case and 2) the raising of moai from a horizontal position is inconsistent with what is known about moai transport based on variation in moai form (Lipo et al., 2013).

Once the pukao had been placed atop the moai, the next step was to change the base of the moai to shift the statue’s center of mass to a point over its base. This step was essential for producing a moai that could stand on its own. To accomplish this task, islanders carved material from the rear of the moai’s base so that its forward lean (critical for transport, see Lipo et al., 2013) was brought to its final, vertical position. Direct evidence of flattening bases to remove the forward lean can be seen on a number of moai (Fig. 13). In these instances, moai bases show two planes representing the initial forward-leaning base surface upon which the statue was “walked” and the secondary base surface created to shift the statue’s center of mass backwards for standing in a stable, vertical position. Ropes may have been used to stabilize the moai during this transition from forward-leaning to vertical, and the pukao base indentation would prevent a pukao placed atop a moai from sliding and toppling forward.

The shifting of a statue from its forward lean to an upright position had implications for the form of the pukao. The road moai, which represent those forms appropriate for transport, include forward lean angles of more than 15° (Lipo et al., 2013). These angles would have resulted in the projection of the pukao center of mass close to the front edge of the base indentation (Fig. 14). In this precarious situation, the pukao base indentation, and specifically the pronounced back edge of this indentation (Fig. 6), would serve to prevent the pukao from toppling forward when the ramp is removed and the moai is brought to an upright, vertical position. Using the three-dimensional models to determine center of mass, we verified this attribute in four well preserved pukao spread between Heki‘i and Anakena.

Once the statue was standing upright, the final step was the removal of the ramp. Stones were often incorporated into the wings of the ahu. As a consequence, there are only a few cases where the physical evidence for ramps remain (Fig. 12).
5. Discussion

The empirical evidence supports our hypothesis that *pukao* transport by rolling up a ramp most parsimoniously explains the archaeological record. The hypothesis is supported by the necessary ramp volumes, the forward lean of road *moai*, and the base indentations in *pukao*. Building a ramp would likely have constituted the greatest task in *pukao* placement. However, it is significant that small numbers of people likely placed *pukao*, consistent with the relatively small number of individuals required for *moai* transport (Lipo et al., 2013).

One of the challenges of fully decoding the evidence related to *pukao* transportation is that various physical and chemical processes have greatly weathered the relatively soft and highly vesicular scoria of *pukao* through time. The degree of weathering limits the detail that can be extracted from further study of *pukao* morphology. While this study records the existing exposed variability, further work may need to examine the surfaces of *pukao* not presently observable.

One area of research that might shed additional light on the evidence related to *pukao* transport is the identification of material deposited within *ahu* structures. Future excavations of *ahu* should examine deposits for evidence of reworking *moai*, reshaping *pukao*, and features that might be uniquely associated with the technology of *pukao* placement. Detailed geophysical study of the distribution of stone boulders, cobbles, and finer sediments in and around *ahu* may also reveal evidence of past ramp features. Teasing apart the multiple events that comprise *ahu* structures is difficult: their form reflects building and rebuilding, and, in recent historical times, stones from many *ahu* have been used in walls and other features associated with sheep ranching.

This study and that on *moai* walking (Lipo et al., 2013) suggest that rope played an important role in transporting colossal stones for monument building on Rapa Nui. The tensile strength of rope made of *Triumfetta semitriloba*, however, is poorly documented, and we lack a clear understanding of the amount of plant material required to make a given length of rope. We also lack information on rope design and structure that might affect the strength of such material. Research designed to fill these gaps in our knowledge may shed additional light on the possible importance of *Triumfetta semitriloba* for rope production on Rapa Nui.

6. Conclusion

We advance the hypothesis that the Rapanui transported *pukao* to the top of *moai* using ramps. In this scenario, an earthen ramp is constructed in front of a forward leaning *moai*, the *pukao* preform is parbuckled and possibly levered up the ramp, the *pukao* is tipped so that its base comes in contact with the top of the *moai*, the *pukao*-topped *moai* is brought to stand upright by modifying the *moai* base, and the ramp material is cleared for construction of the statue platform wings. The cylindrical form of *pukao*, the presence of carved base indentations, and the absence of striations on the bases of *pukao* support the idea that *pukao* were rolled rather than slid into place, and we confirm the physical feasibility of rolling a *pukao* up a ramp. The *pukao* base indentations, combined with information about *pukao* center of mass and the forward lean of *moai*, confirm that a *moai* could be brought to stand fully upright after being capped with a *pukao*. Thus, while physical features of *pukao* do not elucidate all aspects of transport (e.g. the final tipping of *pukao*), we use multiple aspects of the material record to advance our physically-feasible model for *pukao* transport.

When one considers the settlement pattern, cultivation strategies, and evidence associated with the technology needed to carve and move monumental architecture, it is clear that there is little empirical support for the notion that a large population once existed on Rapa Nui. Apart from labor and engineering expertise, *moai* and *pukao* transport required only ropes; few, if any, trees were required for these efforts. The palm-dominated forest lost to deforestation had little economic value, because the palms were unsuitable for making canoes, and people competed directly with rat predation for the nuts (Hunt and Lipo, 2011; Hunt, 2007). Robust alternative explanations related to land clearance for cultivation (Mann et al., 2008) and the effects of rat predation on palm nuts (Hunt, 2007) provide a more compelling account for the loss of the forest over the course of human occupation.

Thus, *moai* and *pukao* production and transport cannot be linked to deforestation, nor can forest clearance for extensive cultivation of agricultural surplus to feed thousands of statue workers, as some have supposed (Diamond, 2005). The evidence for *moai* and *pukao* carving and transport points to activities accomplished by small-scale social groups and not thousands of laborers unified under a powerful centralized chieftdom. In this light, we argue that monumentality does not necessarily imply hierarchical and large-scale social organization that is often assumed for many cases of social complexity worldwide. Instead, we see *moai* and *pukao* carving and their transport as vivid cultural expressions of groups in a challenging and competitive environment (DiNapoli et al., 2017; Hunt and Lipo, 2017). Multiple lines of evidence, including the ingenious engineering to “walk” statues and top them with massive stone hats, point to Rapa Nui as an odd story of success in a most unlikely place.

Data availability statement

MeshLab and PhotoScan files associated with all *pukao* models are available for download at Binghamton University’s open repository (http://orb.binghamton.edu/anthropology_fac/31/). *Pukao* models may be viewed online on Sketchfab (https://sketchfab.com/clipo/models). Photographs are available upon request.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2018.04.011.

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