

THE COLOSSAL HATS (*PUKAO*) OF MONUMENTAL
STATUES: AN ANALYSIS OF *PUKAO* VARIABILITY ON
RAPA NUI (EASTER ISLAND)

by

SEAN HIXON

A THESIS

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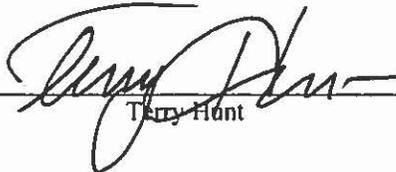
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Terry Hunt

As part of monumental statue (*moai*) construction during the prehistory of Rapa Nui, islanders quarried masses of red scoria, carved them into hats (*pukao*), and placed them atop statues measuring up to 10 meters tall. Despite overall great interest in *moai* and the improbable magnitude of *pukao* that were raised to reach their positions on the heads of statues, few studies have investigated *pukao* production, transport, and placement. This study seeks to analyze three-dimensional variability of *pukao* using 15,000 photos of 50 *pukao* found near statues and 13 red scoria cylinders located in the quarry. These models are used to evaluate which surface features are stylistic with related temporal and spatial variability and which are functional and relate to construction and transport of these multi-ton objects. The functional detail has the potential to shed light on how prehistoric islanders designed *pukao* to be placed atop *moai*. To this end, additional three dimensional models of statue platforms (*ahu*) and *moai* are combined with the models of *pukao* to test the feasibility of the hypothesis that the *pukao* were placed atop *moai* using stone ramps. The hypothesis in which relatively small numbers of Rapanui placed *pukao* atop *moai* by rolling the former up ramps is supported by physical calculations and best explains the archaeological record.

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Table of Contents

Introduction	1
The Conventional Narrative	4
Limited Historic Record of <i>Pukao</i>	6
Speculation on <i>Pukao</i> Meaning	7
Prior Thoughts on <i>Pukao</i> Transport	13
Broad Significance of Research	22
Approach	27
Evolutionary Framework for Understanding Style and Function	28
Applications to <i>Pukao</i>	30
Methods	34
Model Generations	34
Recording Strategy	36
Results	40
Sample Description	40
Issues of Preservation	42
Human Factors	42
The Elements	45
Non-Human Biological Factors	50
Note on Terminology	52
Volume and Weight	53
Base Indentations	56
Physical Form	60
Body	62
Top Cylinder	67
Surface Markings	71
Side Striations	71
Cupules	77

Puna Pau Scoria Bodies	81
Other Sources of Variation	82
Petroglyphs	82
Slabs Missing	91
Basins	93
Englert Numbers	97
Western Text Engravings	98
Conclusion	99
Implications of <i>Pukao</i> Dimensions for Transport	99
Volume	99
Base Indentation	99
Physical Form	100
Surface Variation	101
The Modified Ramp Hypothesis	102
Physics Derivation: Pushing through Levering	105
Physics Derivation: Pulling with Rope	111
Implications of Transport Equations	113
Physics Derivation. Ramp Volume Estimates	118
Implications of Ramp Volume Estimates	121
Modifications to Ramp Hypothesis	125
Future Research	130
Summary	134
Appendix	136
Model Generation, Filing, and Observation Strategies	136
Additional Physics Derivation: Final Flipping of <i>Pukao</i>	138
Bibliography	140

List of Figures

Figure 1 Map showing terrain, major archaeological features, and infrastructure of Rapa Nui.	1
Figure 2. Map showing distances between Rapa Nui and nearest landmasses.	3
Figure 3. Photograph of red scoria quarry at Puna Pau.	3
Figure 4. Photograph of red scoria <i>pukao</i> atop <i>moai</i> on an <i>ahu</i> at Anakena, located on the northern side of the island.	4
Figure 5. Walking of a replica <i>moai</i> at Kualoa Ranch, O’ahu.	6
Figure 6. Engraving based on a 1778 sketch by William Ellis from Hawai’i during James Cook’s Third Voyage.	9
Figure 7. A 1777 engraving based on a sketch by William Hodges from New Caledonia during James Cook’s Second Voyage.	10
Figure 8. Image from Anakena facing W and giving a view of a large scoria body located at a distance from the nearest <i>ahu</i> .	14
Figure 9. William Mulloy’s hypothesized method of prehistoric red scoria body movement on Rapa Nui.	15
Figure 10. Cartoon depiction of a possible rendition of the Ramp Hypothesis.	18
Figure 11. Depiction of the Tower Hypothesis, which involves a pile of stones built beneath the <i>pukao</i> .	20
Figure 12. Depiction of the Simultaneous Set Up Hypothesis in which the <i>moai</i> and <i>pukao</i> are erected simultaneously.	21
Figure 13. Depiction of Wooden Ramp Hypothesis in which <i>pukao</i> is slid up a wooden ramp to the top of a <i>moai</i> .	22
Figure 14. Writers such as Erich von Däniken, whether they intend to or not, often remove the agency of the prehistoric Rapanui in monumental statue production by invoking highly speculative tales of extraterrestrials.	24
Figure 15. A sample of wrenches illustrating stylistic modes that vary from wrench to wrench (e.g., composing metal) and functional modes that are shared by all (e.g. hexagonal notch).	29
Figure 16. Hypothetical changes in frequency of modes under selection versus modes under drift.	32
Figure 17. Illustration of the method behind structure for motion mapping.	35
Figure 18. One of 290 photos (left) used to generate a textured model of <i>pukao</i> 18 at Vaihu in Photoscan (right).	36
Figure 19. Textured model of <i>pukao</i> 18 colored in Meshlab according to the APSS filter in order to highlight surface details.	37

Figure 20. Map showing locations on Rapa Nui that yielded usable models of scoria bodies (green) and locations that include only <i>pukao</i> fragments that were not modelled (red).	40
Figure 21. Graph showing the number of models generated from each location (black) and the number of models at each location that were not modeled (grey).	41
Figure 22. Red scoria reused in Catholic cemetery in Hanga Roa and replica <i>pukao</i> at Tahai.	44
Figure 23. Diagram illustrating expansion of a clay mineral with a sheet structure.	46
Figure 24. Photograph of <i>pukao</i> in intertidal zone at Vaihu prior to salvage efforts during Norwegian Archaeology Expedition in 1955.	47
Figure 25. Photographic panorama of the front of the <i>ahu</i> showing fallen <i>moai</i> and <i>pukao</i> at Tongariki in 1914-15.	49
Figure 26. Photographs of restored <i>ahu</i> at Tongariki with a single <i>moai</i> with restored <i>pukao</i> (top) and nearby alignment of <i>pukao</i> following the 1960 tsunami.	49
Figure 27. <i>Pukao</i> 55 at Tongariki covered in lichen.	50
Figure 28. Undated photograph of sheep roaming Rapa Nui.	51
Figure 29. Chart illustrating the number of scoria bodies within each condition mode and representative samples from the extreme modes.	52
Figure 30. Photographs of the two relatively large cylindrical bodies of red scoria included in the <i>pukao</i> database and not located in Puna Pau that are not considered to be <i>pukao</i> .	53
Figure 31. Volume of <i>pukao</i> plotted as a function of distance from quarry.	54
Figure 32. Cumulative number of red scoria cylinders as a function of distance from quarry.	55
Figure 33. Photograph collected by Métraux of the <i>pukao</i> belonging to Paro at Te Pito Kura.	56
Figure 34. Chart illustrating the number of scoria bodies within each resting face mode, and representative samples of a few of the modes.	58
Figure 35. Sketches of base (left) and side (right) views of <i>pukao</i> and the variables considered.	59
Figure 36. Fragments from engravings based on sketches made by visitors to Rapa Nui during Cook's 1774 visit and La Pérouse's 1786 visit that highlight <i>pukao</i> .	61
Figure 37. Sector division of <i>pukao</i> -bearing <i>ahu</i> made for use in spatial comparisons.	62
Figure 38. Photograph of the noticeably conical <i>pukao</i> 65 at Anakena.	63
Figure 39. One-way analysis of variance and pairwise multiple comparison applied to measures of how oblong <i>pukao</i> body cross sections are between sectors.	65

Figure 40. One-way analysis of variance and pairwise multiple comparison applied to measures of how squat <i>pukao</i> bodies are between sectors.	66
Figure 41. Spatial comparison of <i>pukao</i> body and top cylinder mean dimensions by sector with shape aids for visualization.	667
Figure 42. <i>Pukao</i> 66 at Anakena exhibiting an inverted conical protuberance when viewed from the front.	68
Figure 43. One-way analysis of variance and pairwise multiple comparison applied to measures of how oblong top cylinder body cross sections are between sectors.	70
Figure 44. One-way analysis of variance and pairwise multiple comparison applied to measures of how squat top cylinders are between sectors.	71
Figure 45. Representative samples of a few of the modes within the dimension of side striations.	72
Figure 46. Representative samples of a few of the modes within the dimension of cupules.	77
Figure 47. A watercolor from Linton Palmer's 1868 visit to the island showing a few of the Puna Pau scoria bodies.	83
Figure 48. Various tracings of petroglyphs on red scoria <i>pukao</i> , Puna Pau scoria bodies, and red scoria <i>ahu</i> lentils, organized by location.	84
Figure 49. Various <i>pukao</i> with isolated curved line petroglyphs.	86
Figure 50. Various scoria bodies with closed curved form petroglyphs.	88
Figure 51. <i>Pukao</i> 4 from Vinapu with isolated curved lines, a cupule, and circles at the lower left.	89
Figure 52. Drawing by P. Cristián Arévalo of <i>pukao</i> 41 at Tu'u Tahi with horizontally aligned side cupules.	90
Figure 53. The four <i>pukao</i> that include horizontally-aligned pairs of side cupules near their bases.	90
Figure 54. Four of the <i>pukao</i> that have large slabs missing from the upper body edges.	92
Figure 55. Scoria body 86 from Puna Pau in upper photo at right with concave hollow missing.	93
Figure 56. The two <i>pukao</i> located along the southern coast with basins dug.	94
Figure 57. Shallow excavation conducted by the Norwegian Archaeological Expedition in 1955 around the base of <i>pukao</i> 4.	95
Figure 58. Top views of three <i>pukao</i> with notable circular holes in the center of the upward face.	96
Figure 59. Two scoria bodies with clearly-marked Englert numbers.	98

Figure 60. Two scoria bodies at Puna Pau (77 at left and 80 at right) with engraved Western text.	98
Figure 61. The configuration of a parbuckle.	105
Figure 62. Forces involved in levering a <i>pukao</i> of radius R up a ramp, where θ gives the angle of incline of the ramp.	106
Figure 63. Torques acting on the lever as it pivots around point P.	108
Figure 64. An analysis of the distance d and how it relates to ϕ .	109
Figure 65. Forces involved in pulling a <i>pukao</i> of radius R up a ramp, where θ gives the angle of incline of the ramp.	112
Figure 66. Equation giving the force required to move a <i>pukao</i> up a ramp by pushing with a lever (left, equation 16) or by pulling with a parbuckle (right, equation 18).	114
Figure 67. Applied force required to move <i>pukao</i> up ramps with variable angles of incline at four different <i>ahu</i> (1 = Te Pito Kura, 2 = Vaihu, 3 = Akahanga, and 4 = Ura Uranga te Mahina).	115
Figure 68. Applied force required to pull <i>pukao</i> up ramps with variable angles of incline at four different numbered <i>ahu</i> (1 = Te Pito Kura, 2 = Vaihu, 3 = Akahanga, and 4 = Ura Uranga te Mahina).	117
Figure 69. A ramp with an angle of incline of θ , height h, width w, and length a.	118
Figure 70. Equation for the volume of a ramp.	121
Figure 71. Ramp volume as a function of ramp angle of incline.	122
Figure 72. Scale sketch by Heyerdahl and Ferdon showing the extent of the <i>ahu</i> at Te Pito Kura.	123
Figure 73. Spread of stones at the <i>ahu</i> at Ura Uranga te Mahina measuring about 13 meters in length.	125
Figure 74. Image illustrating the convergence of two flat surfaces (marked with black lines) on a fallen <i>moai</i> base just east of Tongariki.	126
Figure 75. Scale sketch showing an approximation of a reasonable ramp coming off of the front of a forward-leaning <i>moai</i> at the Vaihu <i>ahu</i> .	127
Figure 76. Sketch of side view of <i>moai</i> and <i>pukao</i> showing the vertical projection of the <i>pukao</i> center of mass (CM) when given a forward <i>moai</i> lean angle of phi.	129
Figure 77. Textured model of <i>pukao</i> 57 from Hekii showing the pronounced back edge of its base indentation (about 4 centimeters deep) in the upper right and the relatively indistinct front edge of its base indentation near the center.	130
Figure 78. Various dating methods and their effective ranges.	133

List of Tables

Table 1. List of various uses and reuses of red scoria on Rapa Nui.	13
Table 2. Five proposed <i>pukao</i> transport mechanisms with their supporters and basis through time.	16
Table 3. The <i>pukao</i> transport hypotheses listed in Table 2 and expectations for associated wear.	28
Table 4. Dimensions and modes of categorical variables.	38
Table 5. Summary of explanations as to why scoria bodies in given locations were not effectively modelled.	42
Table 6. Distances and ratios of distances between <i>pukao</i> features and centers of mass.	60
Table 7. Tapering in the diameters of <i>pukao</i> with the form of truncated cones.	63
Table 8. Tapering in the inverted conical protuberances of two <i>pukao</i> .	68
Table 9. Comparison of number of scoria bodies with all sides exposed and striations present within each sector relative to total number of scoria bodies with all sides exposed within each sector.	73
Table 10. Comparison of number of scoria bodies without all sides exposed and striations present within each sector relative to total number of scoria bodies without all sides exposed within each sector.	73
Table 11. Abundances of different types of side striations within each sector for scoria bodies with all sides exposed.	74
Table 12. Abundances of different types of side striations within each sector for scoria bodies of all resting faces.	74
Table 13. Results from Fisher tests of individual side striation mode abundances between sectors.	75
Table 14. Overall abundances of the three types of side striations when considering all scoria bodies and only those with fully exposed sides separately.	76
Table 15. Comparison of number of scoria bodies with cupules present within each sector relative to total number of scoria bodies within each sector.	78
Table 16. Abundances of different types of cupules within each sector for scoria bodies of all resting faces.	79
Table 17. Results from Fisher tests of individual cupule mode abundances between sectors.	79
Table 18. Observation matrix listing intersections of side cupule and condition modes.	81
Table 19. Comparison of petroglyph presence on scoria bodies by sector.	85

Table 20. Comparison of closed curved form petroglyph presence on scoria bodies by sector.	687
Table 21. Estimated absolute scale values for dimensions of <i>pukao</i> , <i>moai</i> , and <i>ahu</i> at four locations used in sample physical calculations graphs.	114
Table 22. Estimated absolute scale values for <i>ahu</i> dimensions.	122
Table 23. Uncalibrated measurements between <i>pukao</i> features and centers of mass.	129
Appendix Table 1. List of past visiting groups with references to <i>pukao</i> .	136

Polynesians first colonized the island in approximately 1200 AD and subsequently constructed monumental statues (*moai*) primarily from tuff, which they placed upon platforms (*ahu*) prior to European contact (Hunt and Lipo 2006). Islanders additionally placed cylindrical bodies of red scoria (*pukao*) atop many of the completed *moai*. The Rapanui¹ quarried bodies of stone for *moai* and *pukao* at Rano Rarako and Puna Pau (Figure 3), respectively and subsequently transported them to *ahu* located primarily along the coast (Figure 4). Based on obsidian hydration dating, Sue Hamilton (2013, 100) suggests activity at the Puna Pau quarry between the 14th and 17th centuries (2013, 100). Unlike the tuffaceous *moai*, the *pukao* are made of a relatively soft and less dense scoria that geologist Mark Bandy (1937, 1605) describes as “coarsely vesicular, vesicles ranging up to over 15 cm in diameter. The color varies from bright red, on weathered surfaces, to almost black on fresh fractures. Much of it is ropy and scoriaceous.” The density of the red scoria at Puna Pau is approximately 1.55 g/cm² (Edwards et al. 1996).

¹ Rapanui refers to the people of Rapa Nui.



Figure 2. Map showing distances between Rapa Nui and nearest landmasses. Satellite imagery provided by Google, SIO, NOAA, U.S. Navy, NGA, GIBCO, Landsat, and INEGI, 2015.



Figure 3. Photograph of red scoria quarry at Puna Pau (photo by author, 2014).



Figure 4. Photograph of red scoria *pukao* atop *moai* on an *ahu* at Anakena, located on the northern side of the island. Note that red scoria here is also used in the *ahu* lentils in front of the *moai* (photo by Terry Hunt, 2015).

The Conventional Narrative

The monumental statues on Rapa Nui, coupled with the lack of surface flowing water, sparse vegetation, and small population on the island, perplexed several early European visitors to the island. To many, it seemed impossible for the natives' former statue cult to thrive on an island so deprived of running water and forests. Starting with the English expedition to Rapa Nui under Captain James Cook in 1774, European visitors began to theorize that the island was fully forested and had a more abundant water supply prior to European contact. Specifically, naturalist Georg Forster believed that the Rapanui were "formerly more numerous, more opulent, and happy" (Kahn 1968, 340). To explain the current state of the island, French Captain Jean François Galaup de la Pérouse concluded in 1786 that the "imprudent" ancestors had destroyed

their freshwater and forest resources through total deforestation of the island (Passos 1995, 55). Many subsequent visitors to Rapa Nui adopted similar conclusions. Most recently, Jared Diamond points to Rapa Nui prehistory as a case where islanders committed ecological suicide (termed “ecocide”) prior to European contact (2005). Diamond’s popular judgment of the island’s precontact past advances the historical trend of denying the past accomplishment of the Rapanui. However, research by several archaeologists, led by Terry Hunt and Carl Lipo, has entirely undermined notions of ecocide on Rapa Nui (see Hunt and Lipo 2011). Specifically, Diamond’s ecocide narrative fails to fully consider the effects of post-contact disease and slavery on the native population and overlooks the Rapanui’s sophisticated subsistence strategy.

A key component in Diamond’s ecocide narrative involves *moai* transport. There exist several ideas that explain *moai* transport, but Diamond holds that the need for timber to fuel a statue building mania led to the total deforestation of Rapa Nui (2005, 118). In a recent study of the form of *moai*, Lipo et al. (2013) establish that *moai* transport took place by walking erect statues and that this process did not require timber (Figure 5). This discovery held significance both in dispelling the ecocide myth and in recognizing the ingenuity of the prehistoric Rapanui.



Figure 5. Walking of a replica *moai* at Kualoa Ranch, O’ahu (photo by Terry Hunt, 2012).

Limited Historic Record of *Pukao*

Despite the great interest in *moai*, few studies have investigated *pukao* production and transport. Indeed, Bahn (1993, 84) notes that “The question of how these massive squat blocks were lifted meters off the ground and fixed accurately on the statue heads remains one of the most tantalizing enigma’s of Easter Island’s ancient culture.” Rapa Nui has a turbulent history that has resulted in a loss of indigenous knowledge, so we must turn to the archaeological record in order to answer most questions about prehistoric monumentality. The historical turbulence started with the likely introduction of disease with early European visits to the island and reached its peak during Peruvian slave raids in the mid to late nineteenth century (Fischer 2005, 61). The first slave raid came in 1805, when New England whalers aboard the ship *The Nancy* kidnapped 22 islanders (Charola 1994, 25). Subsequent whalers visiting the

island likely introduced syphilis (Charola 1994, 25). The largest slave raid to the island came in 1862, when eight Peruvian slaving ships anchored off Rapa Nui. According to Thor Heyerdahl and Edwin Ferdon (1961, 67) of the Norwegian Archaeological Expedition of 1955-56:

“[The slave raiders] all decided to cooperate, and eighty armed men were sent ashore spreading trade goods on the ground to attract the natives. When about five hundred of the Easter Islanders were gathered, mostly on their knees examining the trade goods, the slave raiders fell upon them and captured two hundred, while nearly a dozen were shot dead.... Among those kidnapped were the island king, Kaimakoi, and his son Maurata, as well as nearly all the *maori*, or learned men, all of whom died on the guano islands.”

Following international outcry against the brutal Peruvian slave raids, Peruvian slavers repatriated fifteen Rapa Nui. However, those who returned “brought a smallpox epidemic to the rest of the island populations” (Heyerdahl and Ferdon 1961, 68).

Overall, a series of population declines and the loss of the Rapanui intelligentsia led to a significant loss of indigenous knowledge by the time of the first ethnographic work on the island. Though Wilhelm Geiseler (1882) and Katherine Routledge (1914-15) provide some relatively early ethnographic work, the majority of such work came a generation or more after the devastating slave raids and thus provide only partial insight into Rapa Nui’s past.

Speculation on *Pukao* Meaning

Given the loss of traditional knowledge surrounding *pukao*, the very meaning of the red scoria bodies atop *moai* is a source of debate. Historically, visitors to Rapa Nui have variously referred to the red bodies of scoria that rest atop the heads of *moai* as crowns (Katherine Routledge), feather diadems (Alfred Métraux), turbans (Métraux),

headdresses (Linton Palmer), wigs (Everard Im Thurn), hats (Wilhelm Geiseler), millstones (Hippolyte Roussel), topknots (or *pukao*, Heyerdahl), and even baskets (Jacob Roggeveen). Serious speculation as to the meaning of these scoria bodies began in the early twentieth-century with the visit of Katherine and Scoresby Routledge in 1914-15. After their visit, the two main ideas that emerged were that the scoria bodies represented either hats or hair, but the latter gained common use in the mid-twentieth century.

Scoresby Routledge (1917, 334) first advances the hat interpretation by noting a parallel with “a hat very commonly worn made of native grass” that is “not dissimilar to that of the images.” Advancing the hat interpretation, anthropologist W.H.R. Rivers asserts that the scoria bodies represent hats associated with “cult of the dead” (Rivers 1920, 301). He links the opposing hair interpretation with the idea that the prehistoric Rapanui fashioned them out of a desire for aesthetic beauty. According to Rivers (1920, 301), religion, and not the drive for aesthetic beauty, is the only “motive strong enough to have led the makers of the statues to add these crowns and transmit the necessity for their manufacture to their descendants.” He supports this speculation by noting the association of scoria bodies with burials on Rapa Nui and by drawing a parallel: “In the Marquesas a great stone is placed as a sign of mourning on the head of the image representing a dead man” (Rivers 1920, 301). Rivers (1920, 304) also acknowledges the presence of headdresses elsewhere in Polynesia (e.g. in the Hawaiian Islands, Figure 6) that are not associated with rituals related to death. H.D. Skinner (1922), of the University of Otago Museum, seeks to support Rivers’ interpretation of the Rapa Nui scoria bodies with a comparison to hats observed in New Caledonia

during Cook's Second Voyage (Figure 7). The writings of Rivers and Skinner appear to be the only ones following those of Scoresby Routledge that defend the hat interpretation.

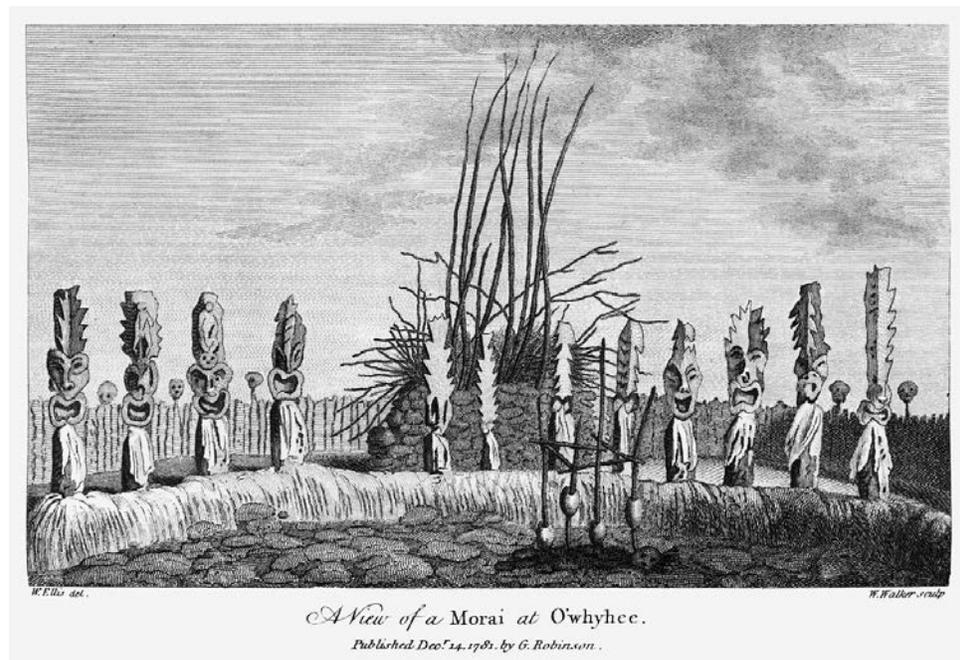


Figure 6. Engraving based on a 1778 sketch by William Ellis from Hawai'i during James Cook's Third Voyage. This depicts a ceremonial platform with figures that may be interpreted as wearing hats. Source: "Heiau." *Wikipedia: The Free Encyclopedia*. Wikipedia Foundation, Inc. 19 Feb. 2012. Web. 20 May 2015.

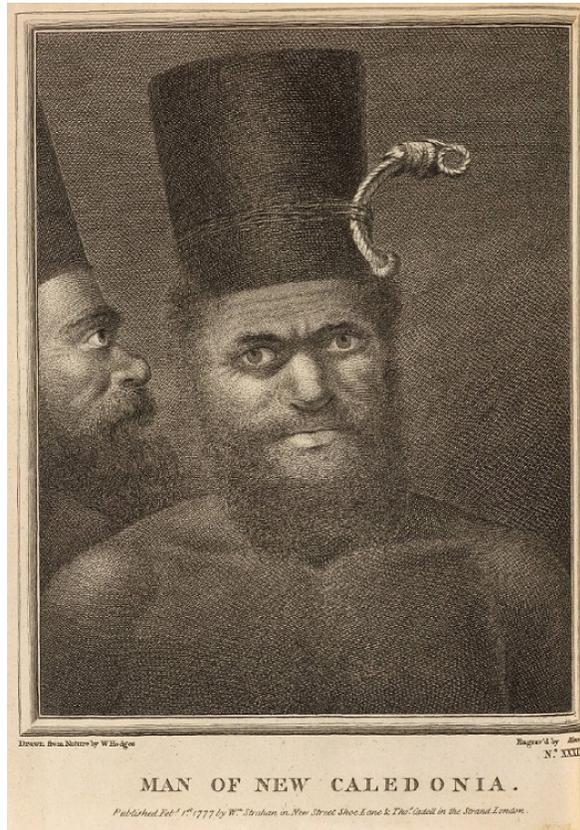


Figure 7. A 1777 engraving based on a sketch by William Hodges from New Caledonia during James Cook’s Second Voyage. This depicts a man in a hat that H.D. Skinner compares to the *pukao* of Rapa Nui. Source: “Man of New Caledonia.” *David Rumsey Map Collection*. 2005. Web. 20 May 2015.

In contrast, archaeologist Henry Balfour (1921, 71) argues that the scoria bodies may be crude imitations of hair that is “lime-bleached after the Melanesian fashion.” Balfour (1921, 71) argues against the hat ideas by noting that Rivers’ connection with the Marquesas is too speculative to be taken seriously. Métraux (1940/1971, 301) generally supports Balfour’s hair interpretation and specifically breaks down Rivers’ connection to the Marquesas by referring to the foremost researchers in the Marquesas, who found no evidence supporting the past use of stone crowns as a sign of mourning.

He notes that “we are by no means sure that the Easter Islanders ever bleached their hair with lime, and they certainly do not have the kinky hair of the Melanesians” (Métraux 1940/1971, 301). Instead, Métraux (1940/71, 301) bases his interpretation on hairstyles popular among the Rapanui: “The cylinder with the knob may have been an attempt to represent the long hair tied up on the head in a big knot (*pukao*), a fashion very common on Easter Island.” Note that the possible mortuary significance highlighted by Rivers and the interpretation by Métraux are not necessarily incompatible, though it is difficult (if not impossible) to know the individual motivations of the builders of the *pukao*. Heyerdahl and Ferdon advance Métraux’s interpretation of the scoria bodies as *pukao*, and the idea that the scoria bodies represent the “islanders’ hairdo” is now firmly entrenched (Charola 1994, 23).

Hamilton’s *Rapa Nui Landscapes of Construction Project* (2007, 2011, & 2013) describes the most recent work with *pukao* completed as part of a broader project examining the significance of Rapanui stone use in general. Work by Hamilton et al. (2011) discusses the varied uses of red scoria and speculates on the past symbolic importance of stone to the prehistoric Rapanui. Hamilton et al. (2011) and Van Tilburg (1986) both note the traditional association of the color red with the ceremonial and the sacred as a possible reason for the quarrying of vibrant red scoria from Puna Pau. To highlight the significance of red scoria beyond use in *pukao*, Hamilton et al. (2011) note the prehistoric (and possibly historic) use of red scoria in *ahu* lentils (see Figure 4) and crematoria. Regarding the link between red scoria and funerary rituals, Hamilton et al. (2011, 183) write, “crematoria associated with *ahu* contain spreads of small fragments of red scoria, mixed with pieces of white burned bone, dark flow lava and sometimes

obsidian flakes.” Noting this association and the absence of red scoria from domestic structures, Thomas (2014, 104) also suggests “an association [of red scoria] with death and funerary rites,” which echoes Rivers’ interpretation of past *pukao* meaning.

Overall, to Hamilton et al. (2011, 186), red scoria *pukao* production is part of a larger series of “material chains of signification from an incredibly monumental scale down to that of a grain of scoria in a cremation.”

Building on Hamilton’s work, Thomas (2014) attempts to understand the distribution of *pukao* and why the Rapanui selected red scoria from Puna Pau for *pukao* production. Thomas also provides an exhaustive list of the various uses and reuses of red scoria on Rapa Nui (Table 1) and a list of descriptions of the various red scoria rock outcroppings on the island. Thomas (2014, 107) also speculates on the prehistoric governance of red scoria quarrying on Rapa Nui by noting a parallel: “Analogous specialized use of stone from particular sources is closely paralleled on Hivaoa, in the Marquesas, where a quarry used for *tiki* and building stone used in sacred structures was governed by a strict *tapu*, and it is suggested that the use of Easter Island red scoria was controlled in a similar way.” None of the research conducted by Hamilton or Thomas examines *pukao* production and transport, even though they address the distribution of red scoria and possible significance of various stone uses on Rapa Nui.

Site type	Puna Pau red scoria	Unspecified	Other red scoriae
<i>Ahu</i>	Topknots (common) Dressed blocks in front (common) Granules in core (common)	<i>Moai</i> pupils (rare)	Dressed blocks in rear (common) Formless lumps in core
<i>Ahu</i> crematoria	Granules (very common)		Granules (sparse–common)
Boathouses	Kerbstones (rare) Pavement (rare)		Kerbstones (sparse)
Inhumations	Topknots (sparse) Formless lumps (very common)		Granules (rare – one on Poike)
Garden features	Stone mulches (rare individual stones)		Stone mulches (very common) <i>Manavai</i> (rare)
Other	Aberrant <i>moai</i> (sparse) <i>Taheta</i> in topknots (rare) Rock art on topknots and <i>ahu</i> facia blocks (sparse) <i>Umu</i> (rare – Anakena only)	Aberrant <i>moai</i>	Aberrant <i>moai</i> (common)

Table 1. List of various uses and reuses of red scoria on Rapa Nui (after Thomas, 2014: 96).

Prior Thoughts on *Pukao* Transport

Many early visitors to Rapa Nui marveled at the fact that multi-ton bodies of red scoria rested atop many of the *moai*. However, most visitors have dedicated time to writing about, rather than investigating, the method of prehistoric *pukao* production and transport. Historical sources agree that the Rapanui moved red scoria from Puna Pau to various points along the coastline by rolling it in relatively large cylindrical bodies. The support for this comes from the fact that some of these relatively large cylinders are found at inland locations between Puna Pau and coastal *ahu*. In particular, Katherine Routledge (1919/1998, 199) notes that “An unwrought cylinder is still lying at a hundred yards from the *ahu* of Anakena.” William Mulloy (1970, 17) also recognizes this scoria body (Figure 8) and claims that it is about 150 meters inland of the nearest *ahu*.



Figure 8. Image from Anakena facing W and giving a view of a large scoria body located at a distance from the nearest *ahu* (Ahu Ature Huke, photo by Terry Hunt, 2015).

Heyerdahl and Ferdon (1961, 373) also refer to two isolated specimens “far away from any *ahu* or statue, apparently abandoned during transport in the general direction of Anakena.” While Lipo and Hunt (2005) have provided thorough documentation of *moai* transport roads, no one has yet attempted a mapping of *pukao* transport roads, likely due to lesser imprint left by the latter stone bodies. Given that only a few red scoria bodies seemingly abandoned in transit remain, it is difficult to determine how the Rapanui rolled them in the past. However, Mulloy (1970, 15) notes that “an encircling groove to be seen on several other topknots presumably in transportation suggests that the operation might have been assisted, at least in some cases, by the mechanical advantage of a cable rigged as a parbuckle.” Overall, he posits that the Rapanui used a combination of pulling and levering as depicted in Figure 9.

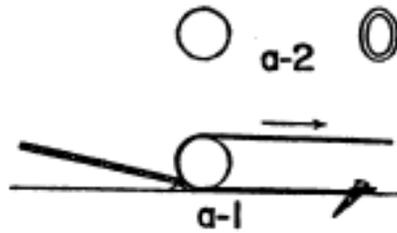


Figure 9. William Mulloy's hypothesized method of prehistoric red scoria body movement on Rapa Nui (a-1) and notice of transition from circular to oblong section (a-2, after Mulloy, 1970: 16).

Opinions diverge when we come to how the massive scoria bodies are transformed into *pukao* and erected on *moai* upon reaching the *ahu*. Generally, Heyerdahl and Ferdon (1961, 373) and Katherine Routledge (1919/1998, 199) share the idea that the prehistoric Rapanui created more refined *pukao* out of the larger scoria bodies only once the latter reached the *ahu* so as to reduce potential damage to the *pukao*. Unlike the larger scoria bodies abandoned in transit, *pukao* include more delicate features such as cylindrical protrusions from the top and base indentations that fit the heads of *moai*. Mulloy further supports the idea of *pukao* carving at *ahu* by contrasting the elliptical sections of the *pukao* with the relatively circular sections of larger scoria bodies (Figure 9). Also note that Steadman et al. (1994, 85) found an exotic red scoria deposit (with an associated radiocarbon date of ca. A.D. 1220-1420) that they hypothesize to be “debitage from the final preparation of topknots” in a test pit just off the seaward side of Ahu Naunau at Anakena. It is very likely that some type of recurring took place near *ahu* in order to create *pukao*.

Transport Mechanism	Supporters	Basis
Rolling Up Ramp	James Cook (1774)	Speculation
	Hippolyte Roussel (1866)	Tradition
	William Thomson (1886)	
	Katherine Routledge (1914)	
	Alfred Métraux (1940)	
Building Tower Beneath	Thor Heyerdahl (1955) Vincent Lee (2012)	Speculation
Raising <i>Pukao</i> with <i>Moai</i>	Thor Heyerdahl (1955) William Mulloy (1970)	Speculation + Base Inden. Horizontal <i>Moai</i> Transport
Wood Sliding Ramp	Pavel Pavel (1995)	Speculation and Experiment
Zig-Zag Ramp	Pavel Pavel (1995)	Speculation

Table 2. Five proposed *pukao* transport mechanisms with their supporters and basis through time.

What follows is a summary of the history of thought by visitors to Rapa Nui regarding *pukao* transport to the top of *moai* (see Appendix Table 1 for list of historic sources that include mentions of *pukao*). As seen in Table 2, all of the ideas put forth include a degree of speculation. Cook (1777, 295) provides the earliest speculation of *pukao* transport: “a sort of mount or scaffolding would be made, upon which they might roll the cylinder, and place it upon the head of the statue; and then the stones might be removed from it.” Cook acknowledges that this speculation is not grounded in any observations that he or his crew made during their stay on the island, yet the Ramp Hypothesis (Figure 10) reappears in the writings of many subsequent visitors. It first reappears in vague terms in the writings of the French missionary Hippolyte Roussel, which refer to a traditional view that the *pukao* were “put on top of each statue by piling up stones” (Altman and Morin 2004, 498). Writing twenty years later, William Thomson (1891, 499) of the Smithsonian expedition asserts without reference to

evidence that “The crowns were placed in position upon the heads of the standing images by building a road-way upon which they could be rolled to the proper spot. The clearing away of the incline was the final act. The earth which formed the surface was utilized as garden patches, and the stones which formed the foundation of the roadway were disposed of in building the wing-extensions of the platform.” Katherine Routledge (1919/1998, 197) supports the Ramp Hypothesis by referring to a traditional story regarding a specific *pukao* on the north coast: “Near Paro, the *ahu* where the last statue was overthrown, there is a hillock, and tradition says that a causeway was made from it to the head of the tall figure which stood upon the *ahu*, and along this the hat was rolled.” Métraux allegedly later encountered the more generalized ramp idea when an islander told him “that his ancestors had moved the *pukao* up onto the head of the *moai* by means of a pile of stones placed against the body of the figure” (Heyerdahl 1989, 162).

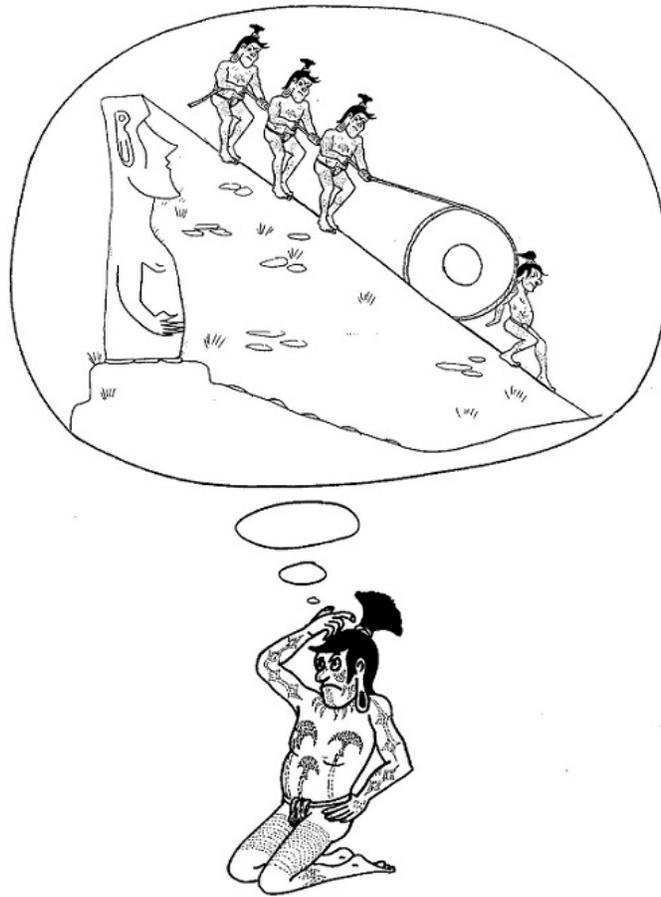


Figure 10. Cartoon depiction of a possible rendition of the Ramp Hypothesis (sketch by Roberto Foester for Pavel Pavel's manuscript, obtained 2014).

While many visitors subscribe to the Ramp Hypothesis and refer to traditional stories for support, this hypothesis came under criticism during the mid-twentieth century. Specifically, regarding Routledge's story of the *pukao* causeway, Heyerdahl and Ferdon (1961, 373) write that it "has the definite character of folklore" given "the impractically long distance to any nearby hill." Mulloy (1970, 15) elaborates on this impracticality: "To have begun at any nearby hillock such a causeway would have to have been at least 13 metres high and several hundred metres long - seemingly a prohibitive amount of construction." Heyerdahl and Ferdon (1961, 110) more generally note the impracticality of the ramp hypothesis by judging that moving a *pukao* up a

ramp is a “precarious undertaking for the number of men who could have gotten behind it.”

In order to offer an alternative to the Ramp Hypothesis, Heyerdahl and Ferdon put forth the hypothesis that a pile of stones gradually stacked under a *pukao* may have raised it to the top of a *moai* (the Tower Hypothesis). In this situation, the *pukao* rises “vertically with the bottom down by gradually building under it a cone of stones” (Heyerdahl and Ferdon 1961, 110). The *pukao* is then levered laterally into place after it reaches the level of the *moai*. As noted by Mulloy (1970, 16), “This would avoid the delicate problem of tipping the topknot” once it reaches the top of the *moai*. However, based on assumptions of the top diameter of the conical pile (7-9 meters) and the angle of repose of the conical pile (60 degrees from the horizontal), Mulloy (1970, 16) concludes that this method involved a platform of “tremendous size” that would make this method “difficult, but possible.” Vincent Lee (2012) later tries to improve the feasibility of this hypothesis by noting that the base spread of the pile of stones beneath the rising *pukao* could be reduced by reinforcing it with beams of timber (Figure 11).

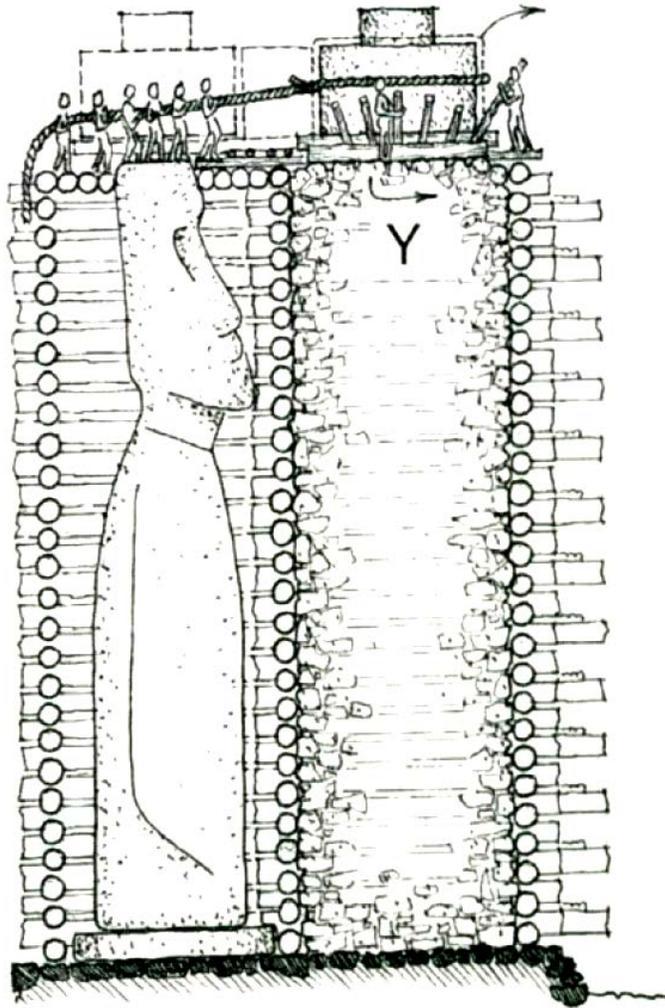


Figure 11. Depiction of the Tower Hypothesis, which involves a pile of stones built beneath the *pukao* (after Lee, 2012: 13).

Heyerdahl and Mulloy offer a third hypothesis, which assumes that the *moai* and *pukao* are erected simultaneously as a unit (the Simultaneous Set Up Hypothesis, Figure 12). In this situation, wooden beams extending along the head of the *moai* and the length of the *pukao* are lashed together in order to affix the *pukao* to the top of the *moai* while both lie on the ground (Mulloy 1970, 16). They are “then raised together by continually maintaining their relationship through adjustments in the single developing wedge of masonry under them” (Heyerdahl and Ferdon 1961, 110). In 1998, Van

Tilburg demonstrated the physical feasibility of this transport idea by using it to erect a 680 kg replica *pukao* with a 9 metric ton replica *moai* (T Ralston personal communication to C Lipo, 2015). While this hypothesis effectively meshes *pukao* transport with the erection of a horizontally-transported *moai*, we now know that the *moai* were ‘walked’ erect to *ahu* (Lipo et al. 2013), which brings this hypothetical *pukao* transport method into question.

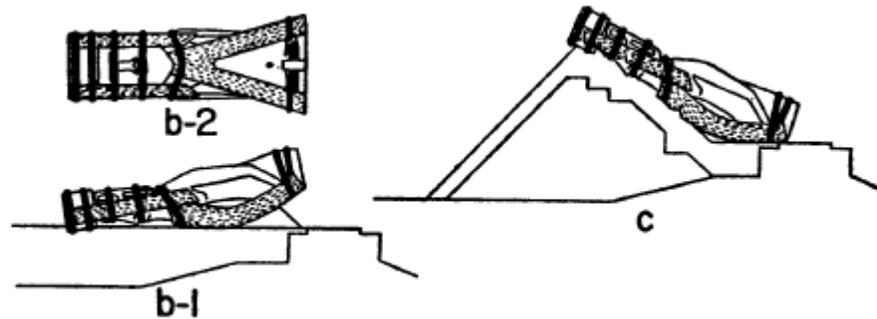


Figure 12. Depiction of the Simultaneous Set Up Hypothesis in which the *moai* and *pukao* are erected simultaneously (after Mulloy, 1970: 16).

Believing in a vertical form of *moai* transport, engineer Pavel Pavel advances a fourth hypothesis for *moai* transport: The Wooden Ramp Hypothesis. He envisions two sloping beams of wood providing a ramp to the top of the *moai*, as shown in Figure 13. In this situation, levering and pulling brings the *pukao* to the top of the *moai*. Pavel demonstrated the feasibility of this hypothesis by using it in with the assistance of four people in order to raise a 900 kg replica *pukao* along two spruce logs to the top of a replica *moai* at three meters height (Pavel 1995, 71). Pavel’s discussion of *pukao* transport involves another speculative method: The *pukao* is rolled side to side up the zig-zag path of stones in what is essentially a compressed version of the ramp

hypothesis. However, Pavel does not provide evidence in support of this hypothesis, and it appears only in his writings.

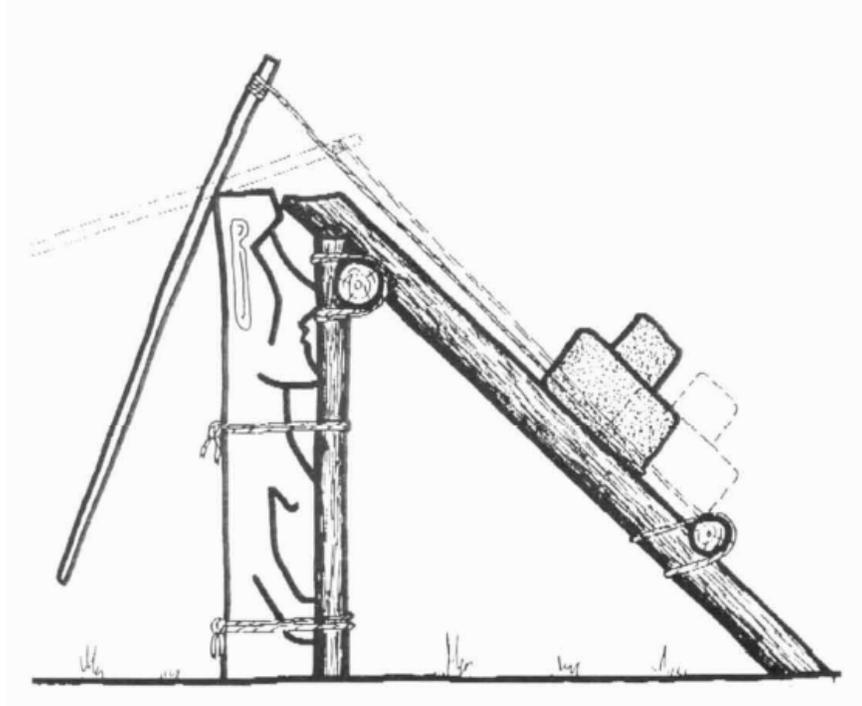


Figure 13. Depiction of Wooden Ramp Hypothesis in which *pukao* is slid up a wooden ramp to the top of a *moai* (after Pavel, 1995: 71).

Given Pavel’s successful experimental work with *pukao* transport in 1994, one might be tempted to say that he “solved the problem of raising a topknot on a statue long ago” (Love 2000, 116). However, showing how the *pukao* could have been transported is not equivalent to showing how they were transported. Neither Pavel nor Mulloy nor any previous visitors systematically examine the form of the *pukao* for evidence that may be uniquely indicative of one form of transport.

Broad Significance of Research

Thus far, I have briefly introduced the physical setting of Rapa Nui, the monumental statue building of the Rapanui, the loss of traditional knowledge on Rapa

Nui through slavery and disease, and the various ideas by visitors to the island regarding the meaning of *pukao* and possible methods of transport. My research builds on existing knowledge by seeking to understand how the Rapanui produced *pukao* and placed them atop *moai*. My project holds significance in drawing attention away from the association of *pukao* with ecocide, potentially changing our understanding of the role of *pukao* in prehistoric Rapanui survival, and preserving a record of existing *pukao* variation.

Understanding *pukao* production and transport will lead to a better appreciation of the past technological accomplishment of the Rapanui: an appreciation that has been denied until relatively recently. As the Orliacs (1995, 1) note, some people have even “refused to believe that the statues are the result of mere human capabilities.” Specifically, writer Erich von Däniken (1970) denies the achievements of the prehistoric Rapanui in monumental statue production by invoking highly speculative tales of extraterrestrials (Figure 14). Meanwhile, Jared Diamond considers *moai* and *pukao* only within his popular ecocide narrative which judges the prehistoric Rapanui as imprudent. Making a comparison between the *pukao* and modern mansions in order to support his judgment of the *pukao* as a sign of imprudence, Diamond (2005, 98) writes:

“I cannot resist the thought that they were produced as a show of one-upmanship. They seem to proclaim: ‘All right, so *you* can erect a statue 30 feet high, but look at me: I can put this 12-ton *pukao* on top of *my* statue; you try to top that, you wimp!’ The *pukao* that I saw reminded me of the activities of Hollywood moguls living near my home in Los Angeles, similarly displaying their wealth and power by building ever larger, more elaborate, more ostentatious houses.”

This speculation closely matches that of Georg Forster, who believed that, prior to their modern downtrodden state, the Rapanui “could spare sufficient time to flatter the

vanity of their princes, by perpetuating their name by lasting monuments” (Kahn 1968, 340). Overall, in Diamond’s narrative (2005, 118), *pukao* and *moai* stand as remnants of a grim cautionary tale of human recklessness in what is “the clearest example of a society that destroyed itself by overexploiting its own resources.” However, the *moai* no longer represent symbols of societal guilt in part since Lipo et al. (2013) demonstrated the ingenious method of their prehistoric transport, which did not require timber. Comparable work with *pukao* may have a similar effect.



Figure 14. Writers such as Erich von Däniken, whether they intend to or not, often remove the agency of the prehistoric Rapanui in monumental statue production by invoking highly speculative tales of extraterrestrials. Source: “Aliens Transporting Easter Island Moai Statues.” *Easterislandtraveling.com*. Web. 20 May 2015.

Aside from modifying popular judgments of Rapa Nui monumentality, Hunt and Lipo’s research reveals how monumentality on Rapa Nui aided the survival of the Rapanui in a marginal and unpredictable environment. For clarification, we must now

consider the ultimate value of monumentality in an evolutionary sense. As O'Brien and Leonard (2001, 14) note, "It would make little sense to call a circle an adaptation, but it might make sense to call vessel decoration an adaptation within a given setting." Similarly, it would make little sense to call the entity of a *moai* or *pukao* an adaptation, for they are not very handy tools in and of themselves. However, producing and transporting *moai* and *pukao* may be explained in terms of adaptation. Such an adaptation need not be aligned with the overt motivation for the prehistoric Rapanui in monument construction (e.g., possible desires to embellish *moai* with *pukao* for aesthetic, mortuary, and/or religious reasons). Hunt and Lipo (2013, 17) recognize the evolutionary function of *moai* construction when they determined the method of *moai* transport:

"The evidence for *moai* carving and transport points to activities by small-scale social groups rather than the product of laborers unified under a powerful central chiefdom. Here monumentality does not imply large-scale social organization as assumed for many cases worldwide. Instead we see *moai* carving and walking as vivid expressions of costly signaling and evolutionary bet hedging in a competitive environment. Multiple lines of evidence, including the ingenious engineering to 'walk' statues, point to Easter Island as a remarkable history of success in a most unlikely place."

Bet hedging, a common strategy for stock investors (i.e., portfolio diversification), involves suppressing mean fitness in order to decrease variability in fitness through time. This behavior holds evolutionary value in unpredictable environments such as that on Rapa Nui (e.g., Beaumont et al. 2009). In the case of Rapa Nui monumentality, time spent with *moai* production and transport is a form of bet-hedging that takes time away from efforts leading toward rapid and unsustainable population growth (Hunt and Lipo 2011, 134). *Moai* production and transport can also be considered an expression

of costly signaling, which holds benefit for the sender and receiver of an honest signal and evolutionary benefit for the population as a whole (Hunt and Lipo 2011, 132). By linking *moai* to costly signaling and evolutionary bet hedging through an understanding of *moai* production and transport, Hunt and Lipo completely overturn Diamond's interpretation of *moai*: Instead of being symbols of imprudence and societal failure, the *moai* are remains of an evolutionary success story. Determining the method of *pukao* production and transport has yet to be fully explained.

Finally, given the ongoing degradation of *pukao*, my research provides baseline documentation that preserves the existing form of the *pukao*. This parallels work by Kersten et al. (2009), which is part of a movement to start preserving the existing variation of *moai* through laser scanning. The various factors at work in destroying *pukao* (and *moai*) through time will be discussed below.

Approach

Bahn (1993, 84) notes that “Only experiments such as those already carried out in carving, moving, and erecting the *moai* can hope to enlighten us” when it comes to understanding *pukao* production and transport. However, experimentation such as that by Pavel can only reveal what is feasible and what is not. In my project, I adopt the approach of Lipo et al. (2013) in their study of *moai* transport and seek to understand *pukao* transport based on evidence in the archaeological record (i.e., to explain variability in that record, and not to speculate about plausible reconstructions alone).

In this study, I treat the various aforementioned ideas on *pukao* transport as hypotheses to be tested through a systematic investigation of *pukao* variability. Does the variability among *pukao* support one hypothesis above the others? Does the extent of variability among *pukao* work against some hypotheses more than others? In answering these questions, I build up from basic observations in order to test the hypotheses and the traits that we would expect to characterize each (Table 3).

GENERAL METHOD	HYPOTHESIS	PUKAO WEAR				
		Deformation on Base	Horizontal Striations	Vertical Striations	Diagonal Striations	Side Depressions
Rolling and Tipping	Ramp		X	X		X
	Zig-Zag Ramp		X	X	X	X
Sliding	Tower	X	X			
	Wooden Ramp	X	X			
Neither Sliding nor Rolling	Simultaneous <i>Moai</i> and <i>Pukao</i> Set Up			X		

Table 3. The *pukao* transport hypotheses listed in Table 2 and expectations for associated wear. If the Rapanui refinished *pukao* after erecting them, then the expected wear (except for that on the *pukao* base) would be erased. Deformation on the base of *pukao* (including striations and irregular indentations) is expected as a product of sliding a *pukao* on its base. Note that none, one, or a couple of the above methods may have been used by the prehistoric Rapanui.

Evolutionary Framework for Understanding Style and Function

I take an evolutionary approach outlined by Robert Dunnell in his discussion on style and function (1978) in order to understand *pukao* variability across space and through time. Such an approach considers the archaeological record as a residue of the past differential persistence of various artifact traits in a cultural system. I define dimensions as points of variation (e.g., striations present on the sides of *pukao*) and modes as types of variation within each dimension (e.g., vertical, horizontal, or diagonal striations). Note that modes within some dimensions are on a continuous scale (e.g., length measurements). The persistence of various modes depends on how the makers of the artifact in question interact with each other, with the artifact, and with the

surrounding environment. These varied interactions give rise to a distinction between stylistic and functional variability.

Modes within dimensions that are not under significant selective pressure are free to vary to a degree and are termed stylistic. In the case of a series of wrenches (Figure 15), the dimension of composing material may be stylistic. Though a metal with relatively high strength is required to maintain the integrity of the wrench, wrenches may be composed of various iron, copper, and aluminum alloys that are free to vary within reasonable limits. Though often noted as neutral and inexplicable in terms of selection, stylistic variation can still be explained by evolution, explained below (Lipo and Madsen 2001, 304). Additionally, because stylistic dimensions are transmitted across space and through time through the interactions of individuals and are unconstrained by selection, their propagation patterns are “accountable in terms of stochastic processes” (Dunnell 1978, 192).



Figure 15. A sample of wrenches illustrating stylistic modes that vary from wrench to wrench (e.g., composing metal) and functional modes that are shared by all (e.g. hexagonal notch). Source:“Wrench.” *The Typology*. Diana Zlatonovski. 2010-2013. Web. 20 May 2015.

When a dimension comes under significant selective pressure, modes without selective value fall out of use and the overall variability within the dimension decreases. The modes that persist due to their selective value are termed functional. In the case of the wrenches, the shape of the notch is constrained to hexagonal in order for the wrench to function properly. All wrenches share this functional mode. However, it is crucial to note that function, while it can be related to use, is not equivalent to use. For example, the camouflaged color on a jet fighter is a functional dimension of the plane that is by no means equivalent to the use of the plane. Also note that the term “functional” is limited in drawing a distinction from dimensions that are stylistic and those which are not. This is because stylistic variation also has an evolutionary function in that it acts as a “reservoir of variability, some of which may ultimately acquire adaptive value with changing conditions” (Dunnell 1978, 199). Returning to the example of the painted aircraft for clarification, note that “gray paint may be stylistic in peacetime, while serving as camouflage during combat” (O’Brien and Leonard 2001, 18). Overall, a consideration of style and function reveals that “Both natural selection and stochastic processes may have a role in explaining cultural change” (Dunnell 1978, 198).

Applications to *Pukao*

I seek to distinguish functional modes of the *pukao* from stylistic modes. The realization that function is not equivalent to use becomes key in considering possible functional dimensions in *pukao*. The overt use of *pukao* from the perspective of the prehistoric Rapanui (e.g., for aesthetic, mortuary, and/or religious purposes) is ultimately unknown. However, the functional detail (exhibiting relatively limited variability) is that which is constrained by the method of transport. In the absence of

evidence to the contrary, I start with the assumption that *pukao* that are currently closely associated with *moai* once rested atop the nearby *moai*. Thus, all *pukao* should share, or should have once shared, functional dimensions. Such sharing of functional dimensions will test the hypotheses in Table 3.

Distinguishing functional modes from stylistic modes will also allow for analysis of the variability of *pukao* that I deem to be stylistic. A robust chronology linked to *pukao* transport does not yet exist, and the relatively small sample size of *pukao* across the island complicates the creation of a *pukao* seriation. Martinsson-Wallin and Crockford (2001) provide a summary of radiocarbon dates for the *ahu* of Rapa Nui, but many dates are based on unidentified charcoal fragments, and none are linked to *pukao* production. In their assessment of radiocarbon dates in East Polynesia, Hunt and Lipo (2006) and Wilmshurst et al. (2011) identify large error stemming from in-built age in many of the radiocarbon samples used in the previous summary of dates. Relative assessments of *pukao* age can be based on condition, but weathering of *pukao* is determined by a multitude of poorly understood variables aside from time (e.g. distance from sea spray, lichen and other biological growths and exposure to wind, sediments transported by wind, and water). Relative to *moai* production, we might assume that *pukao* came late. This stems from reasoning first voiced by Métraux (1940/1971, 302): “If both devices had grown up simultaneously, the use of the big hats would have been more general and would not have been restricted to certain *ahus* or to a few statues on an *ahu*.” Heyerdahl and Ferdon argued that, while relatively old *moai* “have rounded heads and probably were not designed to bear topknots,” younger ones include flat heads that allow for easier *pukao* balance (1961, 215).

The absence of *pukao* dating and limited sample size make it difficult to trace the stochastic processes of style transmission through time in *pukao*. However, I expect that stylistic modes can be distinguished from functional ones in the existing sample based on the limited distribution of stylistic modes versus functional modes (Figure 16). In path A of Figure 16, a mode gradually becomes widespread under selective pressure likely due to functional value that it has in a given selective environment. When this environment changes and the function of this mode is lost, the mode ceases to be transmitted. In path B, a mode does not come under selective pressure, does not become widespread, and is not termed functional. In path C, a mode comes under selective pressure, becomes widespread, and is termed functional. Note that this interpretation does not consider preservation bias and the possibility of the rise in a homogenous style without functional value.

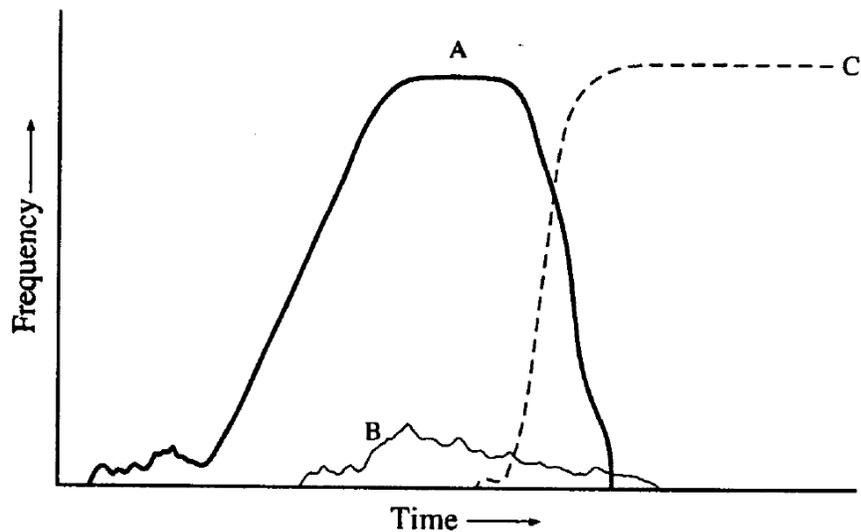


Figure 16. Hypothetical changes in frequency of modes under selection versus modes under drift (after O'Brien and Leonard, 2001: 9).

The present frequency of modes that we observe in the archaeological record (at the endpoint on the time axis in Figure 16) is simply an integral of each mode frequency

over time. I thus consider time as an interval out of necessity and ignore the “noise” in mode frequencies within the given interval. By comparing the behavior of stylistic and functional modes in Figure 16, we quickly find that the two can be distinguished based on their relative abundances. Overall, given our assumption of all existing *pukao* at one point being located atop *moai*, all *pukao* should share the functional modes. Modes that are not shared by all *pukao* will be due to stylistic variability in the absence of other confounding variables such as differential preservation.

Methods

Model Generations

In order to locate and document the *pukao* of Rapa Nui during my visit to the island between May 20th and June 9th, 2014, I relied on a database of *pukao* surveyed with GPS in previous years by teams under Drs. Hunt and Lipo. My documentation consisted of using a couple of Nikon cameras to take approximately 15,000 photographs with embedded GPS coordinates. Using these photos and structure from motion mapping, I generated three dimensional computer models with embedded scale of 53 of the 75 *pukao* and 13 of the 23 Puna Pau scoria bodies identified in the existing database. In the pages that follow, I refer to specific scoria bodies by their assigned number in the existing database. I also worked with Dr. Lipo in recording the physical context of *pukao* at a few *ahu* (at Vaihu, Ura Uranga te Mahina, and Akahanga, on Rapa Nui's southern coast) by collecting aerial photographs with a DJI Phantom quadcopter and using these photos to develop orthophotos through structure from motion mapping.

Structure from motion mapping is an inexpensive form of computerized photogrammetry through which three dimensional structure can be obtained from large sets of overlapping images. The structure from motion software that I use (Agisoft Photoscan 1.0.4, 2014, Agisoft LLC, St. Petersburg, Russia) generates point clouds and meshes by picking out and matching hundreds of thousands to millions of unique points among photos (see section on “Model Generation, Filing, and Observation Strategies” in Appendix). Figure 17 below gives a simplified diagram for visualizing the method behind structure for motion mapping.

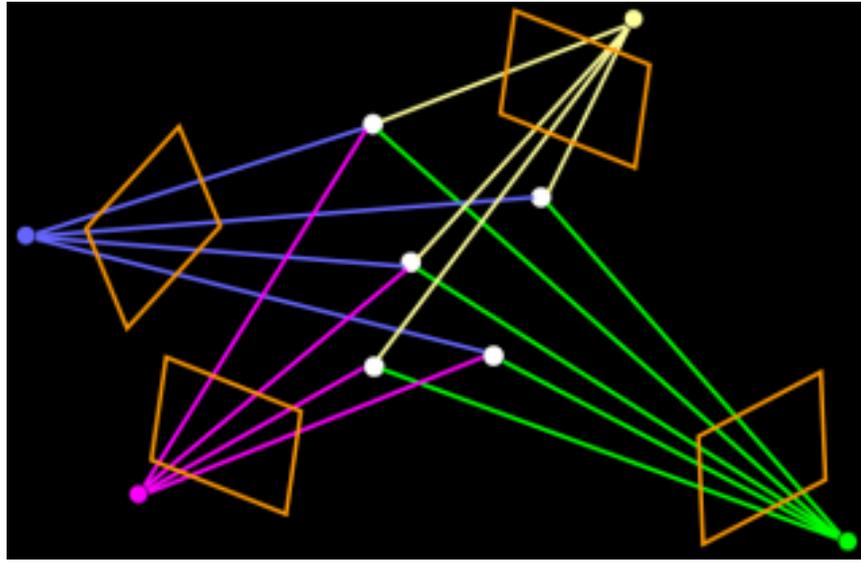


Figure 17. Illustration of the method behind structure for motion mapping. Source: “Globally Optimal Structure and Motion Estimation.” *UCSD Computer Vision*. UCSD School of Engineering. 10 Nov. 2010. Web. 20 May 2015.

When applying photogrammetric mapping to objects, it is important that images cover the entire surface and converge on the object from a close range. The number of photos required to generate a model depends on the size, shape, and texture of the object, but a complete *pukao* model typically requires 50 photos at a very minimum. When created properly, these models preserve color and have sub-centimeter accuracy (Figure 18). In addition to producing highly accurate and inexpensive models that can be easily measured and shared, structure from motion mapping is useful given that it is minimally invasive and fast.



Figure 18. One of 290 photos (left) used to generate a textured model of *pukao* 18 at Vaihu in Photoscan (right).

Recording Strategy

Following the completion of model generations, I recorded surface variations among *pukao* in an open source model-viewing software called Meshlab (Figure 19). A publication by Mudg et al. (2010) provides useful guidelines on how to most effectively identify surface variation of artifacts using three-dimensional imaging. For my work, I used an APSS filter that colorizes curvature. Adjustments in this filter can be made in order to modify the curvature measurement method and the scale of curvature measurement. Applying these filters reveals detail previously obscured by shadow or surface color differences.

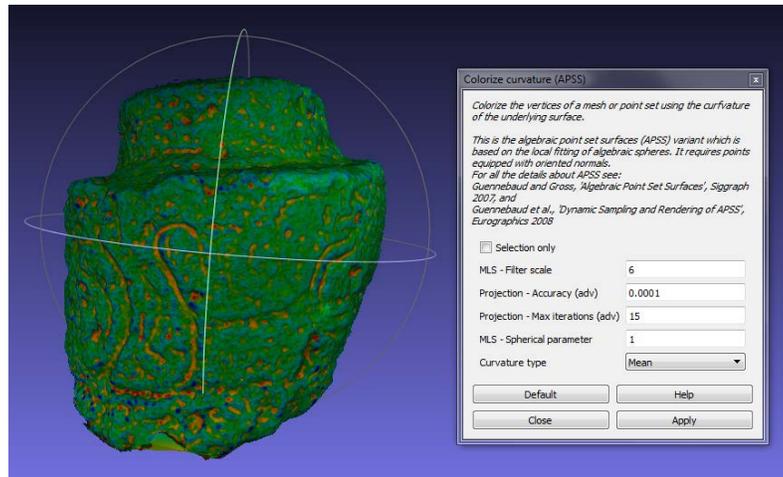


Figure 19. Textured model of *pukao* 18 colored in Meshlab according to the APSS filter in order to highlight surface details.

After a preliminary examination of *pukao* variability, I identified various dimensions of variability and the modes within each dimension. Dimensions with categorical modes are given in Table 4, while those with modes that are continuous variables are listed below:

- Volume
- Maximum body and top cylinder diameters
- Minimum body and top cylinder diameters
- Body and top cylinder heights

Dimension	Mode	Dimension	Mode
Resting Face		Striations Present Along:	
B	Base	H	Horizontal
T	Top	V	Vertical
S	Side	D	Diagonal only
A	Atop Moai	HV	Horiz. and Vert.
BS	Base and Side	HD	Horiz. and Diag.
TS	Top and Side	VD	Vert. and Diag.
		HVD	Horiz., Vert., and Diag.
Condition		0	Not present
P	Poor		
F	Fair	Cupules Present On:	
G	Good	B	Base
E	Excellent	S	Sides
		T	Top
Exposure		BS	Base and Sides
1	Unburied	BT	Base and Top
0	Partially Buried	ST	Sides and Top
		BST	Base, Top, and Sides
Top Cylinder		0	Not Present
1	Present		
0	Absent	Other Surface Markings	
U	Unknown	Cu	Isolated Curved Lines
		Ci	Circles
Base Indentation		Cl	Closed Curved Forms
1	Present	S	Slab Cut Away
0	Absent	B	Basin Dug
U	Unknown	W	Western Text
		E	Englert Number
General Form		x,x,x	Combinations of Above
CY	Cylindrical		
CO	Conical		

Table 4. Dimensions and modes of categorical variables.

I discuss the details of each dimension and mode in subsequent sections.

Currently, it is important to recognize that modes within each dimension are all inclusive and that this stipulates observations for use in paradigmatic classifications.

Paradigmatic classifications of *pukao* will enable me to evaluate which surface features are stylistic with related temporal and spatial variability and which are functional and relate to production and transport.

Paradigmatic classifications are an expedient tool to examine *pukao* variability.

I share the view that “Classifications, or measurement scales, are however, devices of science that are *imposed on*, rather than extracted from, empirical reality. They function

to provide the terms by means of which we identify, describe, measure, and compare phenomena; in short, they allow us to model reality in particular ways for particular purposes” (Dunnell 1986, 152). Unlike definitions for empirical units, artifact classifications define theoretical units (Dunnell 1986, 152). These latter units can be manipulated to fit our needs, and paradigmatic classifications provide a convenient means of gaining this flexibility. Paradigmatic classifications are ones in which the intersection of various attributes form classes. Melinda Allen (1996, 101) gives the following requirements for paradigms in such a classification:

- each class is defined by the same set of criteria: if size is an attribute, then it is considered for all types not just some;
- the attributes are not weighted: no feature is considered more important in type separation than any other;
- the modes are mutually exclusive: only one value can be displayed at a time; and
- the modes are exhaustive: one value must be displayed

Allen notes that classifications founded on this basis are “a particularly parsimonious means of creating analytic units” (1996, 101). Paradigmatic classifications can be easily modified in order to accommodate a potentially infinite degree of variability.

In treating dimensions with continuous modes, I avoid creating arbitrary categorical units based on ranges of numbers and forcibly applying paradigmatic classifications. I instead systematically examine the spread of these continuous modes and their spatial distribution.

Results

Sample Description

The quarry at Puna Pau includes scoria bodies, while finished *pukao* rest in clusters around *ahu* along the coastlines of Rapa Nui. Most locations that yielded usable models are along the southern coast (Figure 20). Only two locations on the island are not represented with models of the scoria bodies present: an unnamed location on the southern coast and relatively remote Vaimata on the northwest coast of the island (Figure 21). Most scoria bodies that were not modeled are from Anakena and Puna Pau.

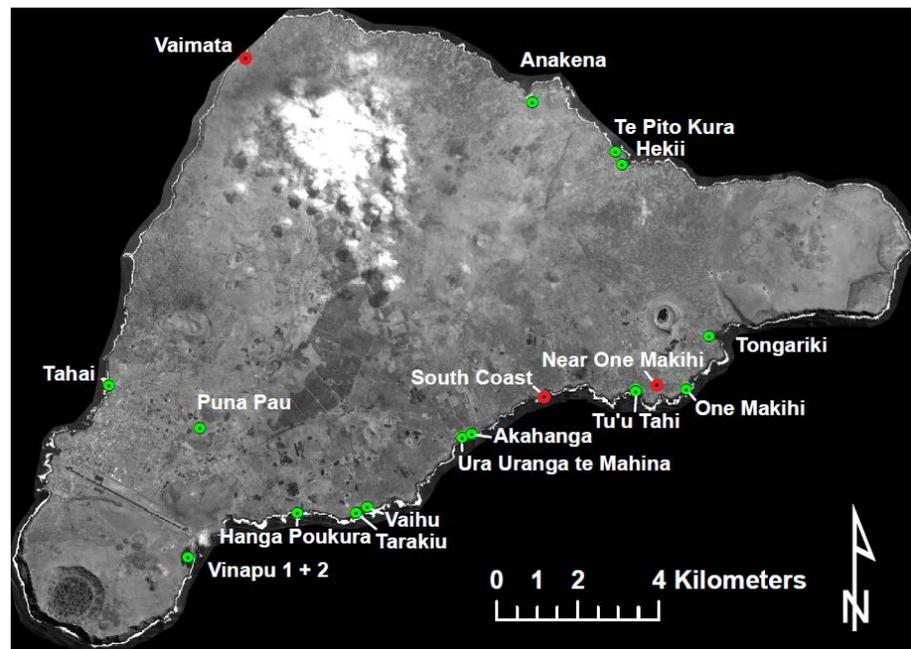


Figure 20. Map showing locations on Rapa Nui that yielded usable models of scoria bodies (green) and locations that include only *pukao* fragments that were not modelled (red). The panchromatic image used in this map is one collected by DigitalGlobe's QuickBird satellite in September, 2005. This image is projected according to the World Geodetic System (WGS) 1984 datum for Universal Transverse Mercator Zone 12S.

Model Development Summary

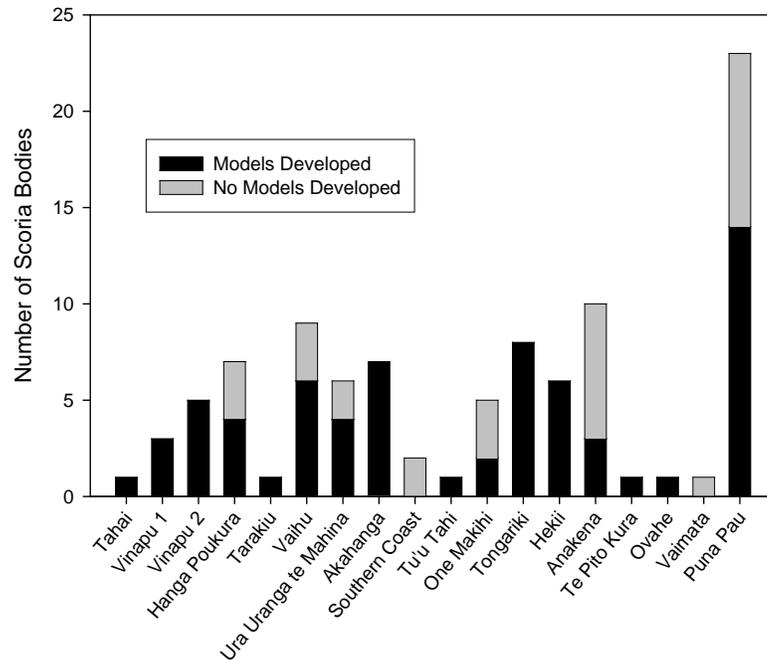


Figure 21. Graph showing the number of models generated from each location (black) and the number of models at each location that were not modeled (grey). Stacked bars give the total number of scoria bodies present at each location.

Most were not modeled due the fact that they were buried, fragmentary, and/or difficult to locate (Table 5). In most cases, heavily eroded fragments of red scoria that clearly composed less than half of an original *pukao* were deemed unusable. There were only a few cases in which complete *pukao* were not modeled. Specifically, *pukao* 66 and 67 on the restored *ahu* at Anakena could not be effectively modeled because overlapping photographs could not be taken of their sides, which are obscured from a ground perspective by the adjacent restored *pukao*.

<i>Pukao</i> Number(s)	Location	Reason(s)
11,12,13	Hanga Poukura	Fragments buried, missing
20,22,24	Vaihu	Fragments missing
30,31	Ura Uranga te Mahina	Almost entirely buried
40	No Data	N/A
42,43	Southern Coast	Fragment buried, missing
45,46,47	Near One Makihi	Fragments missing
63,64	Anakena	Mostly buried, limited access
66,67	Anakena	Incomplete coverage due to restoration
69,70,72	Anakena	Extremely eroded fragments, some missing
75	Vaimata	Almost entirely buried
Nine scoria bodies	Puna Pau	Limited access, tall grass, burial

Table 5. Summary of explanations as to why scoria bodies in given locations were not effectively modelled.

Issues of Preservation

Numerous processes degrade *pukao* through time and thus limit the current sample size. These factors can be divided into those due to humans, the elements, and non-human organisms as described below. *Pukao* are especially susceptible to weathering because they are composed of relatively soft and highly vesicular scoria.

Human Factors

Pukao currently on the ground once rested atop *moai*, so the first major source of damage came with the toppling of *moai*. The role people may have played in toppling *moai* is unclear. Roussel gives the earliest reports of *moai* toppling through warfare in the mid-nineteenth century, but few of Roussel's contemporaries mention such warfare (Edwards et al. 1996, 13). However, Scoresby Routledge (1917, 335) recounts an oral tradition in which "The last one [*moai* with *pukao*] was overthrown by the fathers of the present old men who as boys assisted their fathers – that is, about

1835.” This relatively large *moai* (named Paro) and its relatively intact *pukao* lie near the *ahu* at Te Pito Kura on the northern coast of the island. The fallen *pukao*, such as that belonging to Paro, have remained on the ground ever since, although five (four in Anakena and one in Tongariki) have been restored in the past fifty years. Prior to 1835, visitors to Rapa Nui noted both toppled and erect *pukao*. Even during Cook’s 1774 visit to the island, Johann Forster noted a fallen *pukao*: “We reached the east side of the island, near a range of seven pillars or statues, of which only four remained standing, and one of them had lost its cap” (Kahn 1968, 336).

Once on the ground, islanders reused the red scoria from *pukao* to some degree (see Table 1), and this continued to erode the surviving *pukao*. Note that it is difficult to trace the primary and secondary uses of stone from *pukao* given the varied uses of red scoria through time. Regardless, as Thomas (2014, 106) sensationally puts it, “Over the years, red scoria originally from Puna Pau has been systematically robbed from *ahu*, with topknots cut and gouged away and granules from these spilled like blood over the *ahu* and around the heads of fallen *moai*.” Katherine Routledge (1919/1998, 199) is the first to note reuses of *pukao* “as building materials.” Thomas (Figure 21, 2014, 107) suggests the possible reuse of red scoria in inhumation burials and mentions a *pukao* from the vicinity of Tahai that was incorporated into a cross in the Catholic cemetery in Hanga Roa. Native Rapanui also informed an archaeological team in the 1960s that another *pukao* in the vicinity “had been cut up to use as building material” (Charola 1994, 35). Many headstones in the cemetery are also made of a red scoria ultimately from Puna Pau, but it is unclear as to whether or not *pukao* scoria also contributed to these headstones. The single *pukao* that currently rests atop a restored *moai* at Tahai is

a replica installed between 1968 and 1970 (Figure 22). As Charola (1994, 35) recounts, “a replica *pukao* was set on top of the *moai*, with the intention of removing the topknot after the photographic coverage for an article about the island was completed. But the local inhabitants objected, requesting that the *pukao* be left on the statue, where it remains.”



Figure 22. Red scoria reused in Catholic cemetery in Hanga Roa (left, after Thomas, 2014: 106) and replica *pukao* at Tahai (right, photo by author, 2014). Note that the replica is not considered in any subsequent analysis.

Aside from toppling and subsequent reuse, many scoria bodies have western text engravings (graffiti). However, the damage due to graffiti is minor in comparison to the damage due to red scoria reuse. Most of the graffiti occurs in Puna Pau, and its age is unclear. In 1935, Rapa Nui was designated as both a historic monument and a national park. However, it was not until 1966 that the Chilean government assigned official personnel to the island (Charola 1994, 51). Rapa Nui became a UNESCO World Heritage Site in 1995. Official supervision may dissuade graffiti, but it is still possible that much of the graffiti may be quite recent.

The Elements

During his visit in 1868, Linton Palmer (1869, 374) noted that *pukao* “were much decayed by weather.” By the time of his visit, the *pukao* had already experienced heavy erosion due to a variety of physical and chemical processes independent of human action. Rapa Nui’s coastlines are exposed to the winds, and the island experiences an average of 1,130 mm of rainfall each year, mostly in the form of showers (Charola 1994, 15). It follows that “Heavy showers combined with strong winds erode the stone mechanically” (Charola 1994, 45). In this process, the red scoria weathers to form clay minerals. These weathering products settle in the interstices of the porous scoria and significantly expand when wetted and contract when dried (Figure 23). Accordingly, they create internal stress that aids the breakdown of the rock. Note that the crystallization of salt from sea spray that blows into *pukao* can have a similar affect: one that is commonly referred to as salt wedging.

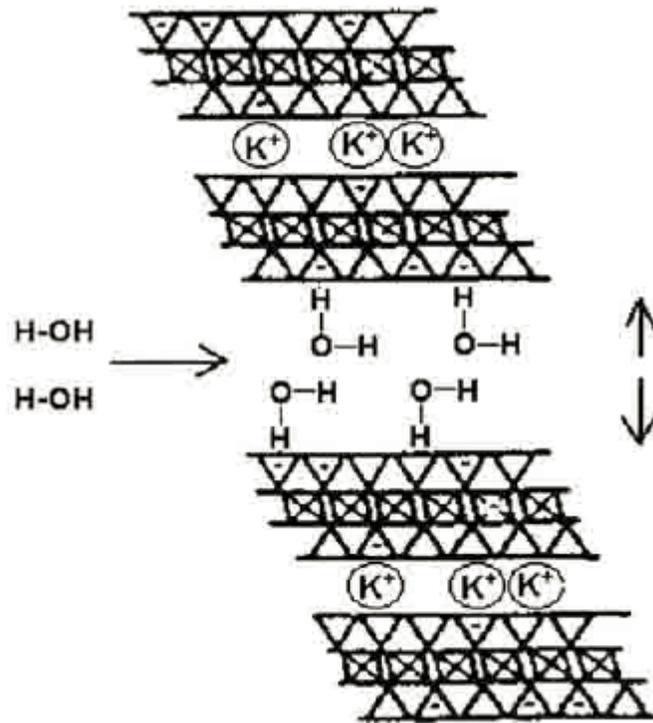


Figure 23. Diagram illustrating expansion of a clay mineral with a sheet structure (after Charola, 1997: 29). Note that water is drawn in between the weakly bonded sheets by attraction between the slight negative charges in the sheets of silicate tetrahedral and the slight positive charges in the hydrogens on the water molecules.

In a few cases, intertidal wave action has significantly eroded *pukao*. A scoria body that might be a possible *pukao* near Ovahe (*pukao* 74) and several *pukao* from Vaihu have been subject to this form of erosion (Figure 24). Spanish visitors to the island in 1770 noted the presence of several *pukao* in the intertidal zone, and this led them to conclude that the “stone of which these columns are made is not native to the island.” (de Haedo 1908, 74). It was not until Cook’s visit to the island four years later that visitors recognized Puna Pau (“a small hollow...with several such cylinders as are placed on the heads of the statues”) as the source of red scoria used in *pukao* production (Ruiz-Tagle 2005, 163). The fact that the Spanish noted *pukao* in the intertidal zone

indicates that these *pukao* likely underwent intertidal erosion for over 150 years. The Norwegian Archaeological Expedition rescued the *pukao* at Vaihu from the intertidal zone in 1955. However, these *pukao* nonetheless exhibit noticeably ablated surfaces.



Figure 24. Photograph of *pukao* in intertidal zone at Vaihu prior to salvage efforts during Norwegian Archaeology Expedition in 1955 (after Heyerdahl, 1989: 39). Note that *pukao* 18 is at center, and that abrasion can be seen toward the base of this *pukao* in Figure 18.

In addition to the slow, persistent onslaught of the elements, cataclysmic natural events such as earthquakes and tsunamis have also aided the breakdown of *pukao*. Rapa Nui is located in an active volcanic zone, and recordings from the seismologic station built on Rapa Nui by the Department of Geophysics of the University of Chile in 1950 reveal that “earthquakes on Easter Island are not isolated events” (Edwards et al. 1996, 2). Edwards et al. examine the stability of *ahu* and conclude that much of the structural damage in *ahu* seen today can be explained by earthquakes. We have direct evidence that at least one tsunami significantly damaged *ahu*. Specifically, in 1960, Ahu Tongariki absorbed the brunt of a tsunami that strew *moai*, *pukao*, and *ahu*

fragments across an area of 1.4 hectares (Charola 1994, 37). Figures 25 and 26 depict Tongariki before and after the tsunami. Wind, rain, clay and salt wedging, earthquakes, and in some cases tsunamis and intertidal erosion have all worked to destroy *pukao* over the years.

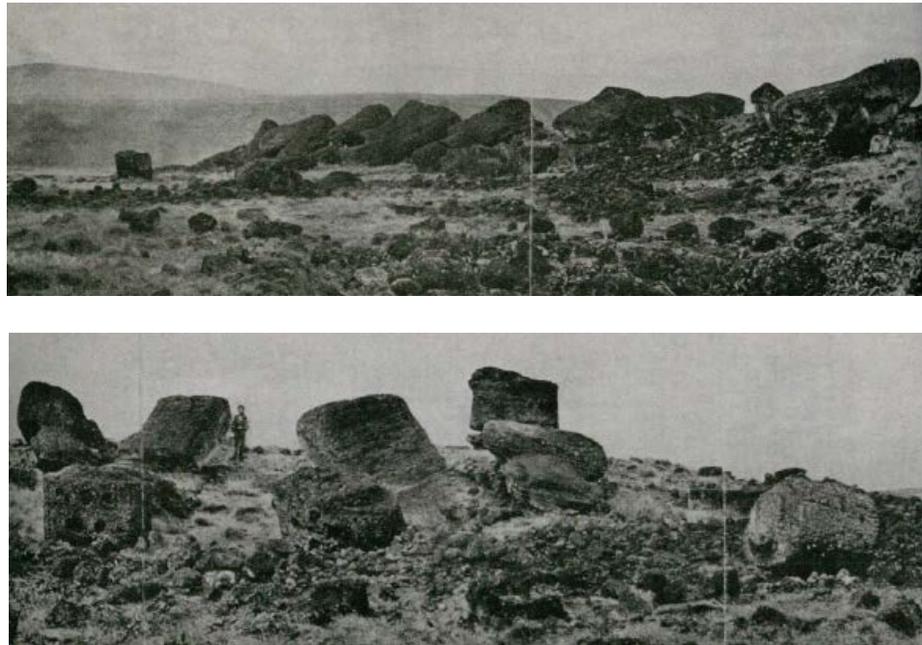


Figure 25. Photographic panorama of the front of the *ahu* showing fallen *moai* and *pukao* at Tongariki in 1914-15 (after Routledge, 1919/1998: Figure 34).



Figure 26. Photographs of restored *ahu* at Tongariki with a single *moai* with restored *pukao* (top) and nearby alignment of *pukao* following the 1960 tsunami (bottom, photos by author, 2014).

Non-Human Biological Factors

Organisms, such as algae, lichens, sheep, cows, and horses have also played roles in the breakdown of *pukao*. Charola (1994, 45) provides a concise description of the roles of algae and lichens:

“These organisms can have a dual action on the stone: they selectively leach out irons, thus weakening the stone matrix, and/or induce mechanical stress by retaining moisture and contributing to the wet/dry cycles of the stone. In the case of lichens, the penetration of rhizines or hyphae causes a mechanical stress that contributes significantly to the detachment of flakes from the stone surface.”

Lichens are particularly good at obscuring and destroying petroglyphs through time given that they have the effect of smoothing edges (Figure 27). Little conservation has focused on removal of lichen from *pukao* given that it is incredibly difficult to remove lichen without crumbling the stone into which its rhizomes have penetrated.



Figure 27. *Pukao* 55 at Tongariki covered in lichen (photo by author, 2014). Note that lichen is also present on the *pukao* in Routledge’s panorama of Tongariki in Figure 25. This indicates that lichen has been a contributing factor in *pukao* degradation for over a hundred years. Generally, lichen appears in greater abundance on *pukao* located in the northeastern portion of the island.

Sheep played a role in the destruction of *pukao* when sheep ranching (primarily organized by the Compañía Explotadora de Isla de Pascua) dominated the island

following the annexation of Rapa Nui by Chile in 1888 and until the island was designated as state property in 1933 (Charola 1994, 27). During this period, the ranch administrators confined the native Rapanui to Hanga Roa and gave sheep free reign of the entire island (Figure 28). The sheep may have damaged intact *pukao*, but they likely had a greater effect in trampling and breaking down smaller fragments of broken *pukao*. Today, grazing animals with access to some *pukao* continue to have damaging affects.



Figure 28. Undated photograph of sheep roaming Rapa Nui (photo by J. Douglas Porteous, 1981).

Overall, these inorganic and organic processes hugely limit the number and condition of intact *pukao* that we see today and highlight the importance of maintaining a record of remaining *pukao* variation. In my analysis of *pukao* variability, I assigned a qualitative condition mode to each *pukao* based on the completeness and symmetry of

each (Figure 29). Note that *pukao* at Anakena include most of the *pukao* in excellent condition but that mode abundances are quite mixed at other locations.

Qualitative Assessment of Scoria Body Condition

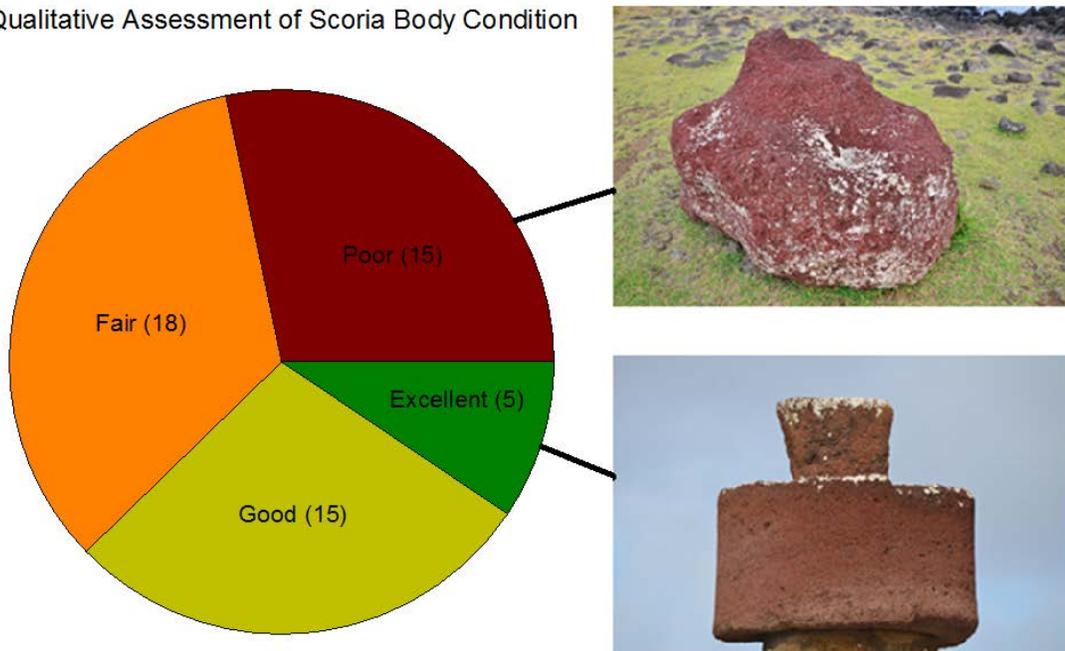


Figure 29. Chart illustrating the number of scoria bodies within each condition mode and representative samples from the extreme modes. *Pukao* 21 is in poor condition, is from Vaihu, and is seen in the upper left corner of Figure 24 prior to its removal from the intertidal zone. *Pukao* 66 is in excellent condition and is from Anakena (photos at right by author, 2014).

Note on Terminology

In analysis of *pukao* variability, there exist two red scoria bodies included by others in the *pukao* database and not located at Puna Pau that I do not consider to be *pukao* (i.e., finished form). Generally, my criteria for accepting a body of scoria as a *pukao* is that it is cylindrical or conical and closely associated with *moai* at an *ahu*. I refer to red scoria bodies that do not fit this criteria and are not *ahu* lentils as merely red scoria cylinders or bodies of red scoria. When *pukao* and other cylindrical red scoria

bodies are considered together, I refer to the assemblage as one of red scoria bodies.

Two bodies of scoria are exceptionally large and located at quite a distance from *moai* (Figure 30).



Figure 30. Photographs of the two relatively large cylindrical bodies of red scoria included in the *pukao* database and not located in Puna Pau that are not considered to be *pukao* (photos by author, 2014). Scoria body number 71 (left) is located about 150 meters distant from the nearest *ahu* at Anakena. This scoria body was in transport and can be considered unfinished, and thus not a *pukao*. Scoria body 62 (right) is located about 200 meters distant from the nearest *ahu* at Hekii.

Volume and Weight

Photoscan software enables measurements of volume from models with embedded scale, but a variety of factors limits the useable number of volume measurements in this study. First, measurements of red scoria body volume are limited to those with full exposure. Of the models generated, about 80% (42 of 53) are of fully exposed bodies. In a few cases, limited access in the field inhibited accurate volume measurements. For example, coarse models of a few restored *pukao* (56 at Tongariki and 66 and 67 at Anakena) inhibit useful volume measurements. A problem also exists in the embedded scale of models of scoria bodies photographed from afar (e.g. *pukao* 44 at One Makihi, which has an embedded scale that is multiple orders of magnitude off). Though the scales in such models do not correspond correctly to an absolute scale, they

are internally consistent. Most models include some skew in embedded scale, and I calibrated these values by using field measurements taken of *pukao* under the lead of Drs. Hunt and Lipo in previous years. Unfortunately, only 16 *pukao* volume measurements had associated average errors of less than one hundred percent.

Plotting the remaining 16 *pukao* volume estimates against distance from quarry, we find a slight positive correlation (Figure 31). This general increase in volume away from the quarry is also coupled with a relatively sharp increase in the number of red scoria cylinders after passing beyond an 11 kilometer radius of the quarry (Figure 32). It is only after passing beyond an 11 kilometer radius that *pukao*-bearing *ahu* located on the northern coast come into view and contribute to the count of those located on the southern coast.

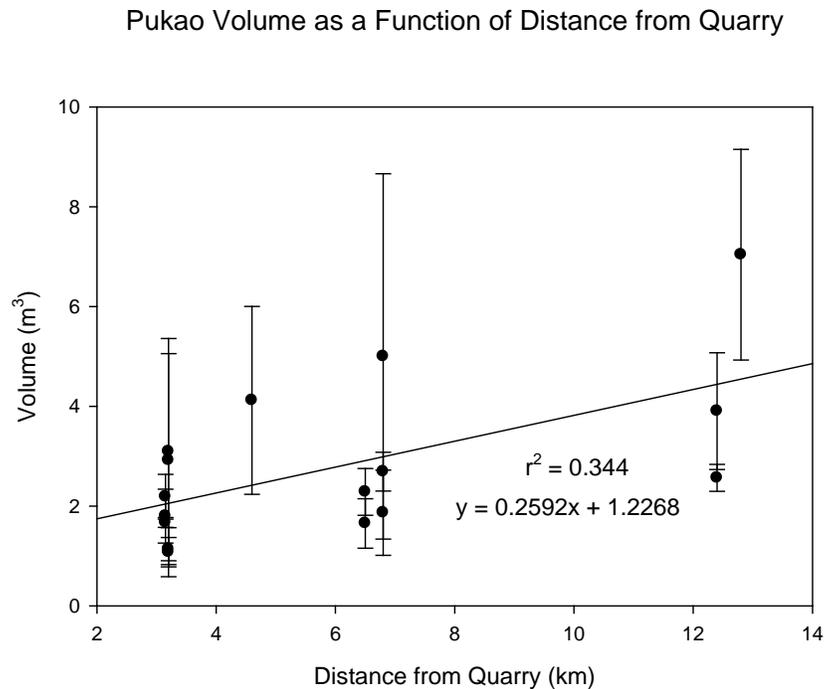


Figure 31. Volume of *pukao* plotted as a function of distance from quarry. Note the insignificant positive correlation.

Numerical Distribution of Red Scoria Cylinders Relative to Quarry

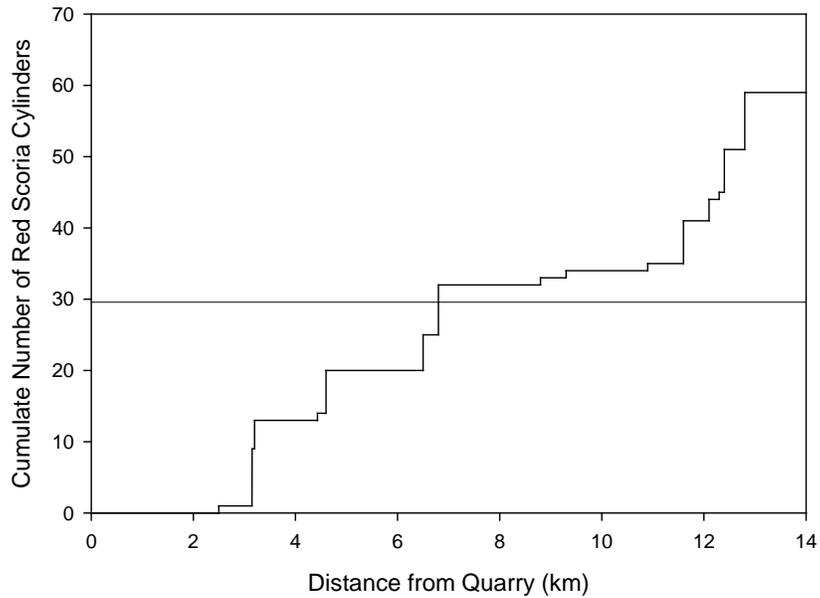


Figure 32. Cumulative number of red scoria cylinders as a function of distance from quarry. Circles of larger radii around the quarry include larger numbers of red scoria cylinders. The horizontal line marks half of the cumulative total. Note the relatively sharp increase in the number of red scoria cylinders after passing beyond an 11 kilometer radius of the quarry.

Given the density of red scoria, determined by Edwards et al. (1996) to be 1550 kg/m^3 , we can calculate the masses of the well-calibrated *pukao*. Unfortunately, only large ranges of possible mass can be gleaned from the calibrated data. The least massive *pukao* in Figure 31 is from Hanga Poukura (*pukao* 14), and it has a mass anywhere between 900 and 2,400 kilograms (kg). The largest *pukao* in Figure 31 is from Tongariki (*pukao* 49), and it has a mass anywhere between 7,600 and 14,000 kg. The most massive *pukao* (*pukao* 73, Figure 33) is at Te Pito Kura, belongs to Paro, and has a mass of about 11,500 kg (Bahn 1993, 84). Overall, *pukao* appear to range in mass between one and almost twelve metric tons.



Figure 33. Photograph collected by Métraux of the *pukao* belonging to Paro at Te Pito Kura (after Métraux, 1940/1970: Appendix).

Base Indentations

When the Spanish visited the island in 1770, they marveled at how *pukao* balanced atop *moai*. F. A. de Agüera y Infanzon (1770/1908, 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.” González y Haedo satisfied their curiosity about how this balance is possible by noting the presence of base indentations in the *pukao*: “I was able to clear up this difficulty on making an examination of another smaller statue from whose head there projected a kind of tenon, constructed to fit into a sort of slot or mortice corresponding to it in the crown; so that by this device the latter is sustained notwithstanding its overlapping the forehead” (Ruiz-Tagle 2005, 58). Few subsequent visitors made further note of *pukao* base indentations, but Heyerdahl and Ferdon (1961, 372) write that, “this depression is not always in the center, but often slightly to one

side, so that the cylinder projected some distance out from above the statue's eyebrows."

Of all of the scoria bodies observed in the field outside of Puna Pau, 42 are indeterminate when it comes to the presence or absence of base indentations. This is accounted in part by poor preservation and exposure but is primarily because many rest on their base, partially buried on their sides, or atop *moai* so that we cannot immediately determine whether or not they include base indentations (Figure 34). All ten of the *pukao* with bases visible include base indentations, and they are located throughout the island (Vinapu, Vaihu, Akahanga, One Makihi, and the Vicinity of Te Pito Kura). In all cases, base indentation depths are only a few centimeters or less. *Pukao 15*, which rests on its side at Hanga Poukura, does not appear to include a base indentation despite its good condition and reasonable exposure. However, note that there is a slight concavity on the base of this *pukao* that may be the weathered remnants of a more clearly defined base indentation. Overall, despite the limited number of observable base indentations and the exception of the *pukao* at Hanga Poukura, *pukao* across the island appear to share base indentations.

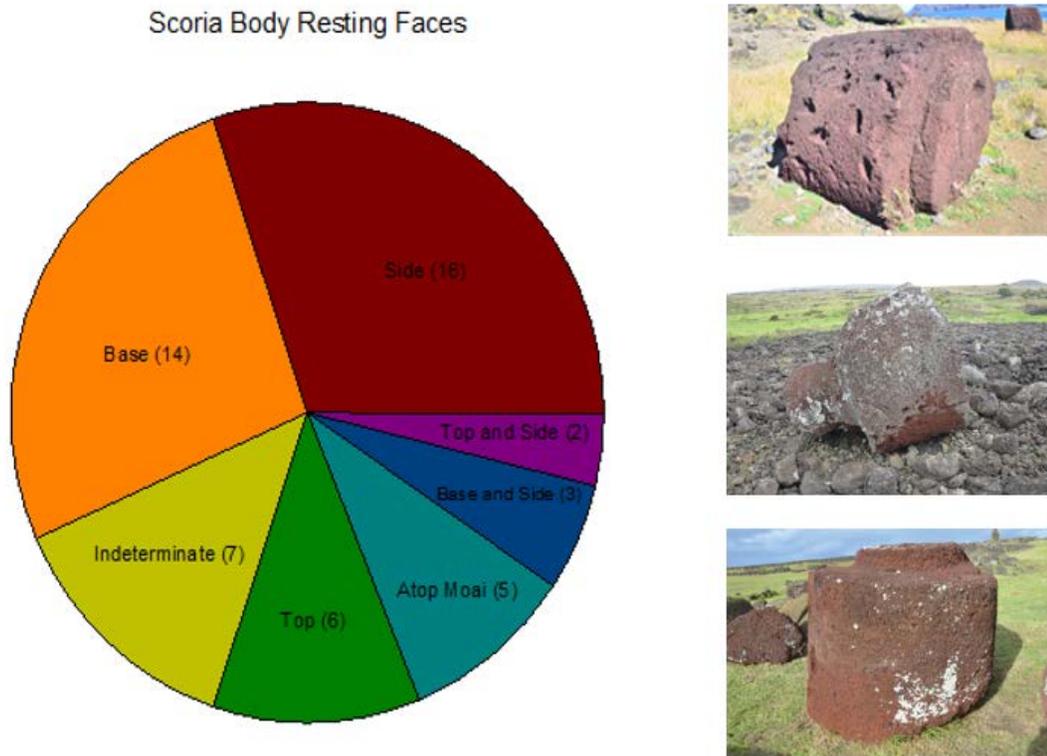
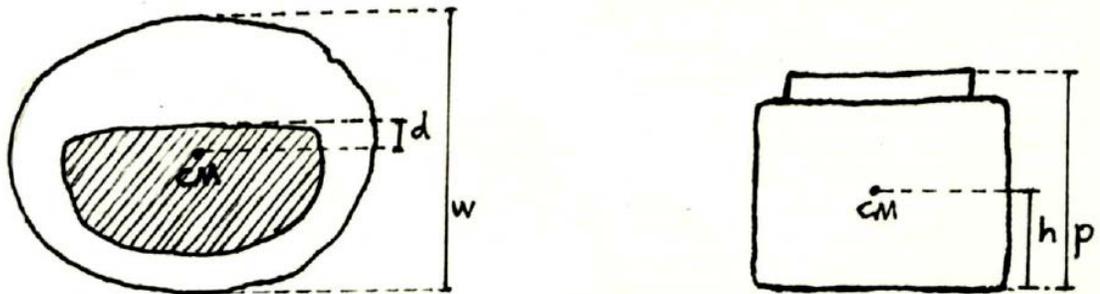


Figure 34. Chart illustrating the number of scoria bodies within each resting face mode, and representative samples of a few of the modes. At right, going from top to bottom, are *pukao* 15 from Hanga Poukura resting on its side, *pukao* 57 from Hekii resting on its side and top, and *pukao* 49 from Tongariki resting on its base (photos at right by author). Note that most scoria bodies with indeterminate resting face are in poor or fair condition. Most indeterminacy stems from confusion over whether a *pukao* is resting on its base or top.

We can gain some understanding of how *pukao* balanced atop *moai* given base indentations as well as the centers of mass of these *pukao*. Specifically, note that *pukao* are unstable when they rest atop *moai* and their center of mass is situated outside of the footprint of the base indentations (Figure 35). I calculated the centers of mass of *pukao* models in Meshlab. Two of the ten *pukao* with clearly visible base indentations, both of which are located at Hekii, have reasonable condition and full exposure that enable

useful center of mass measurements (Table 6). Table 6 also includes center of mass measurements from two *pukao* resting atop *moai* at Anakena that may have base indentations but lack measurement calibrations.

Overall, note the variability in how close the two *pukao* at Hekii are to tipping due to horizontal instability. In *pukao* 57, the center of mass is 23 ± 2 cm from the edge (about 14% of total width of *pukao*) and in *pukao* 60, it is just 19 ± 3 cm from the edge (about 43% of total width). The center of mass lies between 40 and 50 percent up the side of the *pukao* considered. Given the position of the center of mass relative to the base indentations of the *pukao*, we find that the indentations are not necessary for balance once the *pukao* are atop *moai*.



d = horizontal distance between center of mass (CM) and forward edge of base indentation
 w = minimum width of *pukao*
 h = vertical distance between base of *pukao* and CM
 p = total height of *pukao*

Figure 35. Sketches of base (left) and side (right) views of *pukao* and the variables considered. Note that the *pukao* will be unstable while resting horizontally atop a *moai* if its center of mass lies outside of the base indentation (shaded) footprint in the left sketch.

Location	<i>Pukao</i> Number	d (cm)	h (cm)	d/w	h/p
Hekii	57	23 ± 2	74 ± 6	0.14	0.44
Hekii	60	19 ± 3	57 ± 8	0.43	0.40
Anakena	65			0.39	0.41
Anakena	68			0.41	0.43

Table 6. Distances and ratios of distances between *pukao* features and centers of mass. Refer to the above diagram and key for clarification of variables. Note that the center of mass lies between 40 and 50 percent up the side of the four *pukao* considered.

Physical Form

Is there any significant spatial variation in the main physical form of *pukao*?

Generally, *pukao* consist of a cylindrical body with an oblong cross section and a top cylinder of smaller minimum and maximum diameters. The maximum body and top cylinder diameters in all cases run parallel to the elongation of the base indentation (Figure 35). Members of Cook's and La Pérouse's expeditions recorded this general form of *pukao* (Figure 36). However, some *pukao* bodies and top cylinders actually appear in the form of truncated cones, which will be discussed in the pages that follow. I divide my results between those regarding the body of the *pukao* and those regarding its top cylinder.

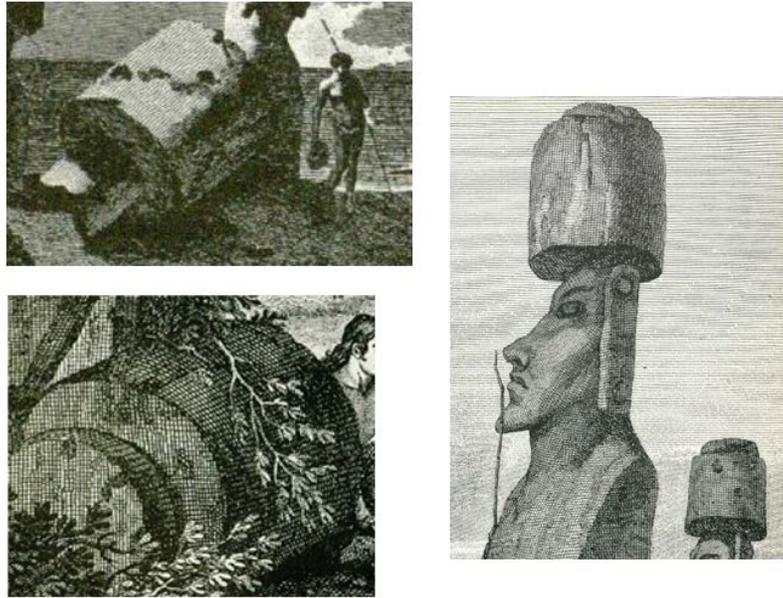


Figure 36. Fragments from engravings based on sketches made by visitors to Rapa Nui during Cook's 1774 visit and La Pérouse's 1786 visit that highlight *pukao*. The upper left image is based on a sketch made by William Hodges during Cook's visit, while the other two are based on La Pérouse's visit (after Heyerdahl and Ferdon, 1961: 54 and 61, respectively).

To characterize the cylindrical form of the *pukao* bodies and top cylinders, I use ratio measures, which serves two functions: (1) it eliminates the aforementioned problem of inconsistent embedded scales between *pukao* models, and (2) it condenses observations. A cylinder with an oblong cross section can be characterized by two ratios. One ratio characterizes how oblong its cross section is (I use minimum diameter over maximum diameter), and the other describes how squat it is (I use minimum diameter over height).

In this and subsequent sections, I group observations from *pukao* at different *ahu* in order to increase sample size in my spatial comparisons. There are many options in choosing spatial units, and the choice of groupings will affect the outcome of any subsequent analyses. However, the division of the *pukao*-bearing *ahu* into the three

sectors shown in Figure 37 is most reasonable considering that it groups natural clusters of *ahu* and maintains reasonable sample sizes in each sector.

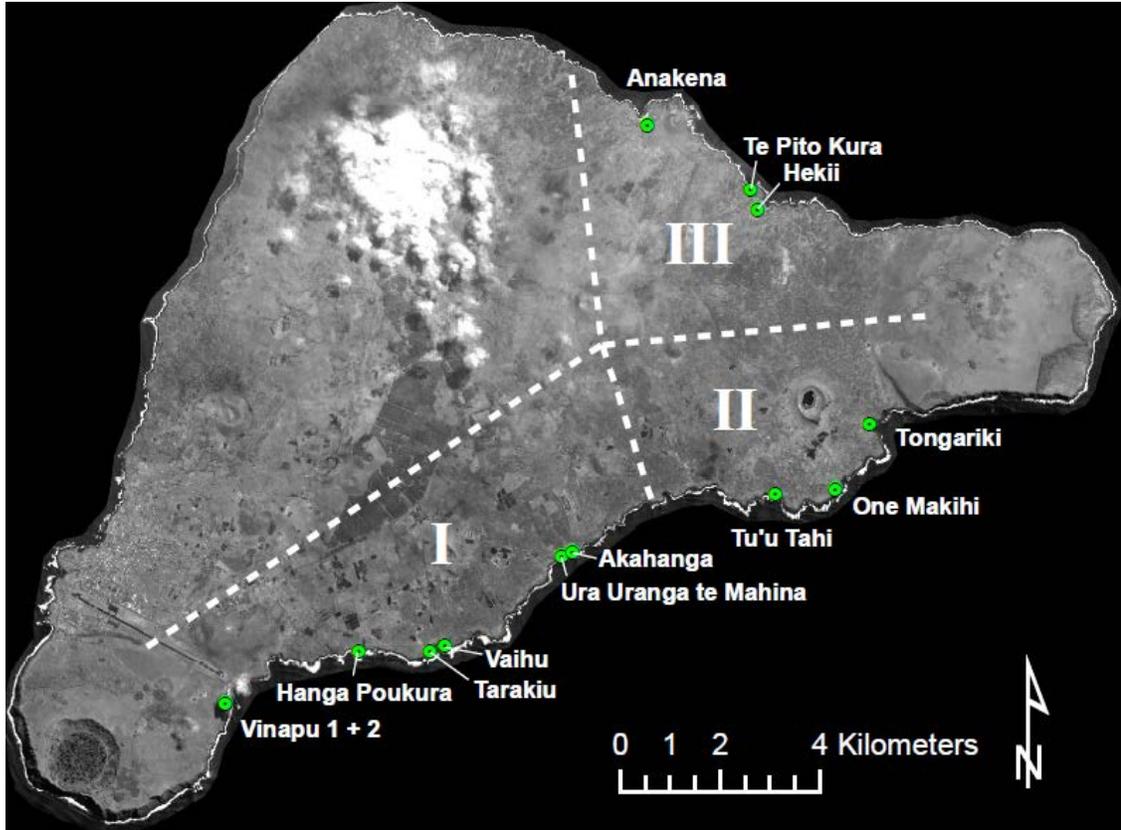


Figure 37. Sector division of *pukao*-bearing *ahu* made for use in spatial comparisons. Note that the exact delineations of sectors are arbitrary as long as they maintain the existing grouping.

Body

Although most *pukao* are cylindrical, *pukao* 65 at Anakena (in Sector III) is noticeably conical (Figure 38). Comparison of the minimum and maximum body diameters on the tops and bottoms of the 53 scoria bodies outside of Puna Pau reveals that a total of six are conical, and these are split evenly between sectors I and III (Table 7). Overall, 10% (3 of 30) of the *pukao* in Sector I have conical bodies, while 30% (3

of 10) of the *pukao* in Sector III have conical bodies. The observed spatial distribution of conical bodies does not significantly differ from expected values (Fisher's exact test in a 2X3 matrix; $p = 0.2266$).

The most conical *pukao* (*pukao* 65) tapers to approximately two thirds of its base diameters toward the top. Tapering is difficult to discern in the field when the top diameter is greater than 80 percent of the bottom diameter. Also note that, for the three *pukao* in Sector III in which both minimum and maximum diameter tapering can be observed, the tapering of the minimum diameter is consistently greater than the tapering of the maximum diameter.



Figure 38. Photograph of the noticeably conical *pukao* 65 at Anakena (photo by author, 2014).

Sector	<i>Ahu</i>	<i>Pukao</i> Number	Top/Bottom Max. Diam. Percent	Top/Bottom Min. Diam. Percent
I	Vinapu 1	8	U	89.22
I	Hanga Poukura	14	85.00	U
I	Hanga Poukura	15	U	92.36
III	Hekii	57	94.22	80.69
III	Anakena	65	67.24	63.10
III	Anakena	68	94.79	91.60

Table 7. Tapering in the diameters of *pukao* with the form of truncated cones. Lower percentages correspond to a greater degree of tapering. Also note that the indeterminate tapering (U) in three cases is due to partial burial and erosion.

Regarding cylindrical scoria bodies, the *pukao* with the most circular cross section (*pukao* 29) is located in Ura Uranga te Mahina (Sector I), with a ratio of minimum over maximum diameter of 0.9901. In contrast, the *pukao* with the most oblong cross section (*pukao* 48) is located in One Makihi (Sector II), with a ratio of minimum over maximum diameter of 0.6070. A comparison of means between sectors (Figures 39 & 41) reveals that the mean value in Sector II ($n = 7$) of 0.695 is significantly lower than both the mean value in Sector I ($n = 13$) of 0.829 and the mean value in Sector III ($n = 7$) of 0.862. In this and subsequent comparisons, I use a one-way analysis of variance and the Holm-Sidak method for pairwise multiple comparisons in order to identify significant differences between means. Overall, *pukao* in Sector II have cross sections that are significantly more oblong than those of *pukao* in the other two sectors. Note that conical *pukao* (14, 57, 65, and 68) are included in this analysis and that diameter ratios at the base of the *pukao* are considered in all cases.

The most squat *pukao* (*pukao* 38) is in Akahanga (Sector I), with a ratio of minimum diameter over height of 1.8815. The most elongate *pukao* (*pukao* 50) is in Tongariki (Sector II), with a ratio of minimum diameter over height of 0.8583. A comparison of means between sectors (Figures 40 & 41) reveals that the mean value in Sector II ($n = 8$) of 1.083 is lower than the mean value in Sector III ($n = 6$) of 1.335 and is significantly lower ($p = 0.001$) than the mean value in Sector I ($n = 17$) of 1.368. Overall, *pukao* in Sector II are significantly more elongate than those in Sector I. Conical *pukao* are again included in this analysis, and diameter ratios at the base of the *pukao* are considered in all cases.

One Way Analysis of Variance

Monday, March 23, 2015, 2:20:21 PM

Data source: Bod Min D / Max D in Stats.SNB

Dependent Variable: Bod Min D / Max D

Normality Test: Passed (P = 0.703)

Equal Variance Test: Passed (P = 0.731)

Group Name	N	Missing	Mean	Std Dev	SEM
I	13	0	0.829	0.0875	0.0243
II	7	0	0.695	0.0707	0.0267
III	7	0	0.862	0.0616	0.0233

Source of Variation	DF	SS	MS	F	P
Between Groups	2	0.116	0.0578	9.600	<0.001
Residual	24	0.145	0.00602		
Total	26	0.260			

The differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = <0.001).

Power of performed test with alpha = 0.050: 0.955

All Pairwise Multiple Comparison Procedures (Holm-Sidak method):

Overall significance level = 0.05

Comparisons for factor: Sector	Comparison	Diff of Means	t	Unadjusted P	Critical Level	Significant?
III vs. II		0.168	4.046	0.000469	0.017	Yes
I vs. II		0.134	3.689	0.00115	0.025	Yes
III vs. I		0.0336	0.925	0.364	0.050	No

Figure 39. One-way analysis of variance and pairwise multiple comparison applied to measures of how oblong *pukao* body cross sections are between sectors.

One Way Analysis of Variance

Monday, March 23, 2015, 2:33:40 PM

Data source: Data 2 in Stats.SNB

Dependent Variable: Bod Min D / Ht

Normality Test: Passed (P = 0.553)

Equal Variance Test: Passed (P = 0.320)

Group Name	N	Missing	Mean	Std Dev	SEM
I	17	0	1.368	0.250	0.0606
II	8	0	1.083	0.179	0.0633
III	6	0	1.335	0.254	0.104

Source of Variation	DF	SS	MS	F	P
Between Groups	2	0.460	0.230	4.171	0.026
Residual	28	1.544	0.0552		
Total	30	2.004			

The differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.026).

Power of performed test with alpha = 0.050: 0.555

All Pairwise Multiple Comparison Procedures (Holm-Sidak method):

Overall significance level = 0.05

Comparisons for factor: Sector

Comparison	Diff of Means	t	Unadjusted P	Critical Level	Significant?
I vs. II	0.286	2.836	0.00839	0.017	Yes
III vs. II	0.253	1.992	0.0562	0.025	No
I vs. III	0.0329	0.295	0.770	0.050	No

Figure 40. One-way analysis of variance and pairwise multiple comparison applied to measures of how squat *pukao* bodies are between sectors.

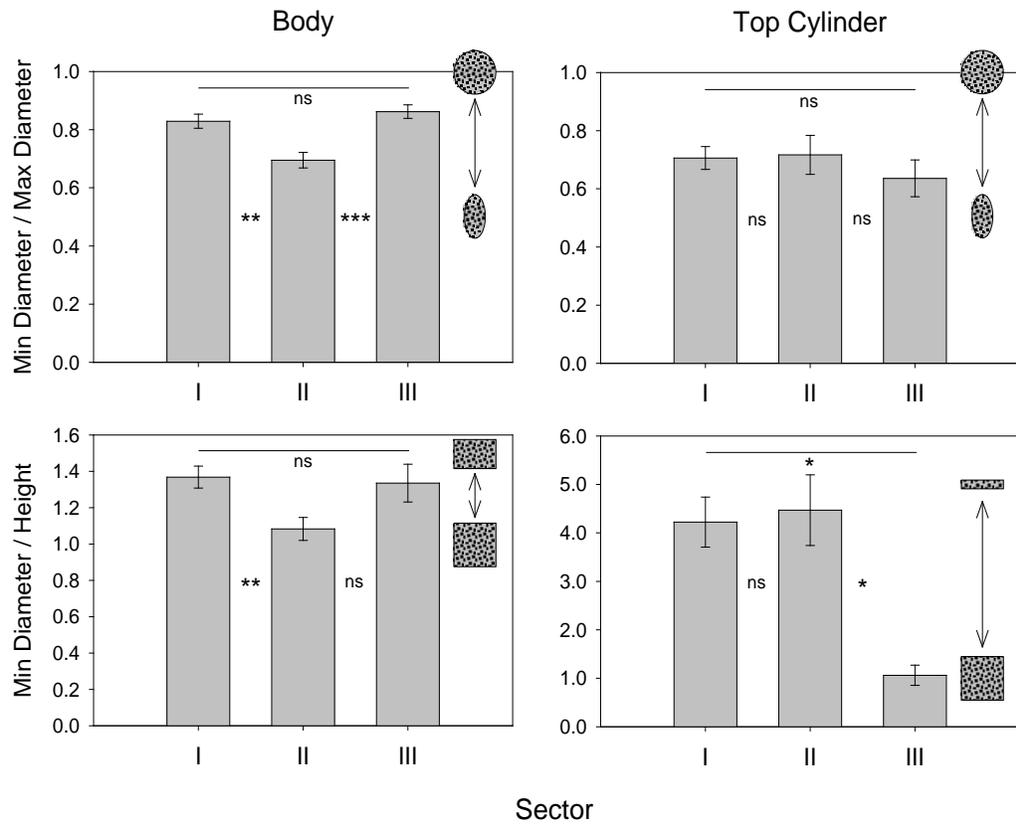


Figure 41. Spatial comparison of pukao body and top cylinder mean dimensions by sector with shape aids for visualization. Statistical significance is denoted by * ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$) and “ns” ($p > 0.05$). Note in particular the dramatically more elongate top cylinders in Sector III.

Top Cylinder

Pukao 65 and 67, both at Anakena, do not have top cylinders, but *pukao* 67 has an irregular top stump that may represent the remnant of a broken top cylinder. With a chi-squared test of limited power, we find that top cylinder presence does depend on sector ($p = 0.0463$) but this dependence is not significant when we consider a more accurate application of Fisher’s exact test ($p = 0.0925$). Although most *pukao* have oblong top cylinders, a few notable exceptions possess truncated inverted oblong top cones (Figure 42, Table 8). Note that all of these exceptions are located in Sector III and that maximum diameter tapers more than minimum diameter in all cases.

Accordingly, the maximum conical angle of incline is observed when viewing these few *pukao* from the front or back.



Figure 42. *Pukao* 66 at Anakena exhibiting an inverted conical protuberance when viewed from the front (photo by author, 2014).

Sector	<i>Ahu</i>	<i>Pukao</i> Number	Bottom/Top Max. Diam. Percent	Bottom/Top Min. Diam. Percent
III	Hekii	57	91.45	96.12
III	Anakena	68	88.15	100.00

Table 8. Tapering in the inverted conical protuberances of two *pukao*. Note that *pukao* 66 also clearly has an inverted conical protuberance but that no model was created for this *pukao*.

Now considering the *pukao* with cylindrical top protuberances, *pukao* 18 in Vaihu (Sector I) has the top cylinder with the most circular cross section with a ratio of minimum over maximum top cylinder diameter of 0.8786. *Pukao* 44 in One Makihi (Sector II) has the top cylinder with the most oblong cross section with a ratio of minimum over maximum top cylinder diameter of 0.4033. A comparison of means between sectors reveals that the mean value in Sector III ($n = 3$) of 0.636 is lower than both the mean value in Sector I ($n = 9$) of 0.706 and the mean value in Sector III ($n = 6$) of 0.717. Although the top cylinders in Sector III appear relatively oblong, none of these differences are significant. Note that the inverted truncated cones atop *pukao* 57 and 68 are included in this analysis, with ratios taken from measurements at the very top

of the *pukao*. The relatively oblong top cylinders in Sector III can be explained by the small sample size in this sector and the fact that the cross section of the inverted cone features becomes more oblong with increasing distance from the *pukao* body.

Significant differences exist in the mean squatness values of *pukao* between sectors. *Pukao* 51 in Tongariki (Sector II) has the squattest top cylinder with a ratio of top cylinder minimum diameter over height of 7.5086. The most elongate top cylinder is found on *pukao* 68 in Anakena (Sector III), with a ratio of top cylinder minimum diameter over height of 0.7073. A comparison of means between sectors (Figures 41 & 43-44) reveals that the mean value in Sector III ($n = 3$) of 1.062 is significantly lower than both the mean value in Sector I ($n = 14$) of 4.222 and the mean value in Sector II ($n = 6$) of 4.470. Overall, top cylinders in Sector III are significantly more elongate than those in Sectors I and II. Note that the top inverted cones of *pukao* 57 and 68 are included in this analysis and that height in these cases still refers to vertical distance between the bottom and top and not the diagonal distance along surface of the cone. Comparing squatness between cylinders and inverted cones through the same ratio is not problematic in this case for two reasons. First, Table 8 reveals that minimum diameter (involved in the squatness ratio) does not change significantly along the height of the truncated cone. Second, the more elongate top cylinders in Sector III would be significantly different from others were we to consider the smaller minimum diameter where the truncated cone meets the *pukao* body.

One Way Analysis of Variance

Monday, March 23, 2015, 2:38:43 PM

Data source: Top Min D / Max D in Stats.SNB

Dependent Variable: Top Min D / Max D

Normality Test: Failed (P < 0.050)

Equal Variance Test: Passed (P = 0.993)

Group Name	N	Missing	Mean	Std Dev	SEM
I	9	0	0.706	0.117	0.0391
II	6	0	0.717	0.164	0.0670
III	3	0	0.636	0.110	0.0634

Source of Variation	DF	SS	MS	F	P
Between Groups	2	0.0142	0.00712	0.397	0.679
Residual	15	0.269	0.0179		
Total	17	0.283			

The differences in the mean values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.679).

Power of performed test with alpha = 0.050: 0.049

The power of the performed test (0.049) is below the desired power of 0.800. Less than desired power indicates you are less likely to detect a difference when one actually exists. Negative results should be interpreted cautiously.

Figure 43. One-way analysis of variance and pairwise multiple comparison applied to measures of how oblong top cylinder body cross sections are between sectors.

One Way Analysis of Variance

Monday, March 23, 2015, 2:45:14 PM

Data source: Top Min D / Ht in Stats.SNB

Dependent Variable: Top Min D / Ht

Normality Test: Passed (P = 0.189)

Equal Variance Test: Passed (P = 0.300)

Group Name	N	Missing	Mean	Std Dev	SEM
I	14	0	4.222	1.930	0.516
II	6	0	4.470	1.785	0.729
III	3	0	1.062	0.363	0.209

Source of Variation	DF	SS	MS	F	P
Between Groups	2	27.562	13.781	4.265	0.029
Residual	20	64.627	3.231		
Total	22	92.190			

The differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.029).

Power of performed test with alpha = 0.050: 0.549

All Pairwise Multiple Comparison Procedures (Holm-Sidak method):

Overall significance level = 0.05

Comparisons for factor: Sector

Comparison	Diff of Means	t	Unadjusted P	Critical Level	Significant?
I vs. III	3.161	2.764	0.0120	0.017	Yes
II vs. III	3.409	2.682	0.0143	0.025	Yes
II vs. I	0.248	0.283	0.780	0.050	No

Figure 44. One-way analysis of variance and pairwise multiple comparison applied to measures of how squat top cylinders are between sectors.

Surface Markings

Side Striations

Are there any spatial patterns in the presence and types of linear striations found on the side of scoria bodies not located in Puna Pau? The modes within this dimension include horizontal striations (H), vertical striations (V), diagonal striations (D), combinations, or complete absence of striations (0, Figure 45). Striations need not

extend across the entire side of a scoria body to be considered in this analysis. Most striations are a couple of centimeters deep, and striations rarely extend to the top or bottom of scoria bodies.

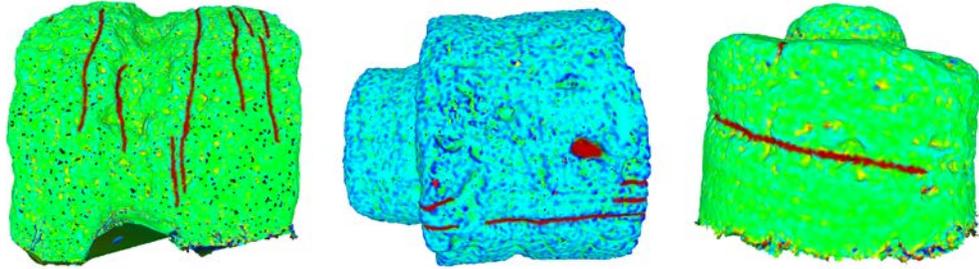


Figure 45. Representative samples of a few of the modes within the dimension of side striations. Scoria body 71 from Anakena (left) with horizontal striations, *pukao* 61 from Hekii (center) with vertical striations, and *pukao* 5 from Vinapu with a diagonal striation.

The analysis of surface striations is complicated by the uncertainty involved in classifying the side striations of scoria bodies resting on their sides. Specifically, a body resting on its side that has no exposed side striations may in fact have striations on its covered surface. Given this uncertainty, I treat scoria bodies that rest with all sides exposed separately from those that do not.

Of the scoria bodies with all sides exposed, about 62% include side striations (Table 9). Sector I includes the greatest percent of bodies with side striations (71%), while Sector III includes the lowest percent with side striations (33%). However, an application of Fisher's exact test reveals that the spatial distribution of scoria bodies with side striations in this sample does not significantly deviate from expected values ($p = 0.4350$).

Of the scoria bodies with not all sides exposed, a lesser percent (50%) include observed side striations, as we would expect (Table 10). In this case, Sector I includes

the greatest percent of scoria bodies with side striations (58%), while Sector II includes the lowest percentage of scoria bodies with side striations (25%). Again, an application of Fisher's exact test reveals that the spatial distribution of bodies with side striations in this sample does not significantly deviate from expected values ($p = 0.5509$). Overall, there is no significant spatial patterning according to sector of scoria bodies with side striations and those without.

Sector	Striated	Total	Striated (%)
I	12	17	71
II	3	6	50
III	1	3	33
Total	16	26	62

Table 9. Comparison of number of scoria bodies with all sides exposed and striations present within each sector relative to total number of scoria bodies with all sides exposed within each sector. Note that an application of Fisher's exact test reveals that the spatial distribution of scoria bodies with side striations in this sample does not significantly deviate from expected values ($p = 0.4350$).

Sector	Striated	Total	Striated (%)
I	7	12	58
II	1	4	25
III	3	6	50
Total	11	22	50

Table 10. Comparison of number of scoria bodies without all sides exposed and striations present within each sector relative to total number of scoria bodies without all sides exposed within each sector. Note that an application of Fisher's exact test reveals that the spatial distribution of scoria bodies with side striations in this sample does not significantly deviate from expected values ($p = 0.5509$).

When we compare the abundances of scoria bodies with different striation combinations between sectors, we find no significant deviation from expected values. This holds true when we consider only scoria bodies with all sides exposed (Table 11) and when we consider scoria bodies of all resting faces together (Table 12). However,

note that the p-values from applying the chi-squared test to the data in the tables below can be misleading. This stems from the fact that chi-squared tests become inaccurate when multiple expected values are less than one and when over 20% of the expected values in the contingency table are less than 5, as is the case in Tables 11 and 12. In such cases, the chi-squared test is less likely to detect differences that actually exist between the observation and contingency matrices.

Sector	H	V	HV	VD	HVD	0	Total
I	1	5	1	4	1	5	17
II	0	2	1	0	0	3	6
III	0	0	1	0	0	2	3
Total	1	7	3	4	1	10	26

Table 11. Abundances of different types of side striations within each sector for scoria bodies with all sides exposed. Note that a chi-squared test reveals that the abundances of different types of side striations in this sample does not significantly deviate from expected values ($p = 0.711$).

Sector	H	V	HV	VD	HVD	0	Total
I	3	8	1	5	2	11	30
II	0	3	1	0	0	6	10
III	0	1	2	0	1	6	10
Total	3	12	4	5	3	23	50

Table 12. Abundances of different types of side striations within each sector for scoria bodies of all resting faces. Note that a chi-squared test reveals that the abundances of different types of side striations in this sample does not significantly deviate from expected values ($p = 0.330$).

In order to more accurately identify any potential spatial patterns by sector in the abundance of scoria bodies with different surface striation classifications, I conducted a series of Fisher exact tests based on the relative abundances by sector of those bodies within a given classification mode and those without. These tests involve 2X3 matrices, with sector number against presence/absence of an individual mode, and I again consider bodies with all sides exposed separate from the total sample of scoria bodies.

Based on Table 13, we find that the existing data suggest that the presence and distribution of different types of side striations is independent of sector.

Striation Type	P (sides fully exposed)	P (all resting faces)
V	0.5941	0.6834
H	1.0000	0.4854
D	0.3332	0.2055
HV	0.7271	0.2320
VD	0.3332	0.3402
HVD	1.0000	1.0000
None	0.4350	0.3188

Table 13. Results from Fisher tests of individual side striation mode abundances between sectors. Note that more general modes (such as V, H, and D, individually) in these tests are taken to include individuals in combination modes (such as HVD). For example, the individual test for vertical striations (V) considers that all scoria bodies within modes of V, HV, VD, and HVD belong to the V mode. The results in this table suggest that the distribution of different types of side striations is independent of sector.

Given the lack of patterning between sectors, we can briefly note the overall abundances of each type of side striation (Table 14). These results indicate that vertical striations are by far the most common, and this tendency is accentuated when we consider only those scoria bodies with sides fully exposed. Significant percentages of scoria bodies have no striations, while a very limited number include diagonal striations. Indeed, no scoria bodies exist with only diagonal striations.

Striation Type	Presence in bodies with fully exposed sides (%)	Presence in all bodies (%)
V or some combination	58	48
H or some combination	19	20
D or some combination	15	10
None	38	46

Table 14. Overall abundances of the three types of side striations when considering all scoria bodies and only those with fully exposed sides separately. Note the relative abundance of vertical striations.

It is possible that the condition of scoria bodies affects the presence of striations. In order to estimate the magnitude of this effect, I conducted chi-squared tests of observation matrices with condition modes against striation modes. These chi-squared tests have the potential to be inaccurate due to the low values in the contingency matrix (previously discussed). When considering all scoria bodies, the occurrence of various striation modes is independent of condition ($p = 0.165$). The same holds true to a greater extent when we consider only the scoria bodies with all sides exposed ($p = 0.653$). Overall, the observed striation modes are not strongly associated with condition modes. This suggests that striations persist despite decreased condition through erosion or that the observed striations are independent of condition because they were applied relatively late in the erosive process. We found that there are no spatial patterns by sector in the presence and types of linear striations found on the side of scoria bodies not located in Puna Pau. However, vertical side striations are by far the most common type of side striation.

Cupules

Do spatial patterns exist in the presence and forms of cupules found on scoria bodies located outside the quarry at Puna Pau? The modes within this dimension include cupules on sides (S), cupules on top (T), cupules on base (B), combinations, cupules on unknown face (U), and absence of cupules (0, Figure 46). Cupules range in depth from 2 to 6 centimeters, have clear edges, and are roughly circular in shape.

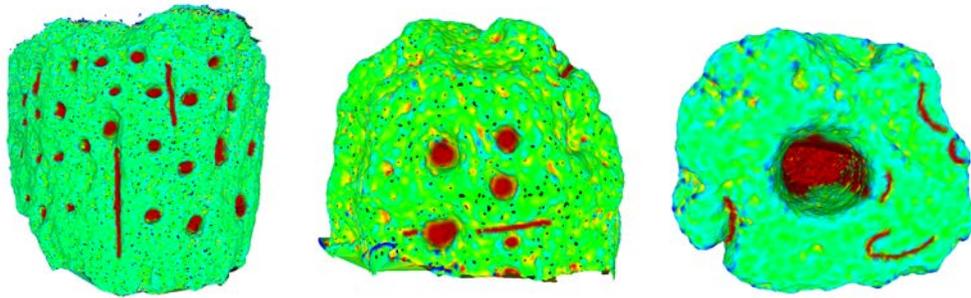


Figure 46. Representative samples of a few of the modes within the dimension of cupules. *Pukao* 73 from Te Pito Kura (left) with side cupules, *pukao* 10 from Hanga Poukura (center) with top cupules, and *pukao* 14 from Hanga Poukura with a base cupule.

As with the analysis of surface striations, the analysis of cupules on the sides of scoria bodies is complicated by the fact that a given body hides the face(s) on which it rests. Specifically, a scoria body resting on its side that has no exposed side cupules may in fact have striations on its covered surface. Because every scoria body has at least one hidden face, bias stemming from resting face is inevitable when we compare abundances of all cupule modes across space. This bias can only be eliminated when we consider the distribution of individual modes that can be clearly assessed across space: Following this method, we only consider bodies that can definitively be assigned membership to a given mode.

Of all scoria bodies surveyed outside of Puna Pau, 80% include cupules present on at least one face (Table 15). Sectors II and III include the greatest percentages of scoria bodies with side striations (both 90%), while Sector I includes the lowest percent of scoria bodies with side striations (77%). However, the spatial distribution of cupules present does not significantly deviate from expected values (Fisher's exact test; $p = 0.4160$).

Sector	With Cupules	Total	With Cupules (%)
I	22	30	73
II	9	10	90
III	9	10	90
Total	40	50	80

Table 15. Comparison of number of scoria bodies with cupules present within each sector relative to total number of scoria bodies within each sector (Fisher's exact test; $p = 0.4160$).

When we compare the abundances of scoria bodies with different cupule combinations between sectors, we find that there is no significant deviation from expected values (Table 16). Unfortunately, as previously discussed, we cannot compare abundances in all modes across space without introducing an unknown degree of bias due to resting face. Also note that, as with the case of side striations, the p-values from applying the chi-squared test to the data in the table below can be misleading. This again stems from the fact that chi-squared tests become inaccurate when multiple expected values are less than one and when over 20% of the expected values in the contingency table are less than 5, as is the case in Table 16.

Sector	S	T	BS	ST	BST	0	Total
I	13	3	1	4	0	8	29
II	6	1	0	1	0	1	9
III	7	0	0	0	1	1	9
Total	26	4	1	5	1	10	47

Table 16. Abundances of different types of cupules within each sector for scoria bodies of all resting faces. Three scoria bodies spread evenly among sectors have cupules on indeterminate faces and so are not included in this analysis. The abundances of different types of cupules in this sample do not significantly deviate from expected values (chi-squared test; $p = 0.436$).

In order to more accurately identify any potential spatial patterns by sector in the abundance of scoria bodies with different cupule modes, I conducted a series of Fisher exact tests based on the relative abundances of those within a given mode and those without (Table 17). Based on these results, the existing data suggest that the presence and distribution of different combinations of cupules is independent of sector.

Cupule Type	P (face fully exposed)	P (all exposures)
S	1.0000	0.4062
T	1.0000	0.7938
B	0.6703	0.4000

Table 17. Results from Fisher tests of individual cupule mode abundances between sectors. Limited samples of scoria bodies with a given face under consideration fully exposed (center column) are considered separately from the total sample including all different types of exposures (right column). Note that the general modes (such as S, H, and D, individually) in these tests are taken to include individuals in combination modes (such as BST). For example, the individual test for side cupules (S) considers that all scoria bodies within modes of S, BS, ST, BST belong to the S mode. Combination modes were not considered due to their minor abundances. The results in this table suggest that the distribution of different types of side striations is independent of sector.

Given the lack of patterning between sectors, we can briefly turn to the overall abundances of each cupule mode. Cupules on the sides of scoria bodies are by far the most common (34 of 50 total, 68%). A limited number of bodies include top cupules (10 of 50 total, 20%), and a very limited number include bottom cupules (2 of 50 total, 4%). No scoria bodies exist with only bottom cupules.

Condition likely affects the presence of cupules. In order to estimate the magnitude of this effect, I conducted a chi-squared test of an observation matrix with condition modes against cupule modes (Table 18). This chi-squared test has the potential to be inaccurate given low values in the contingency matrix (previously discussed). When considering all scoria bodies, the occurrence of various cupule modes is independent of condition ($p = 0.270$). There is a slight tendency of fewer cupules present in scoria bodies with lower condition mode. This may suggest that side cupules are diminished through erosion. However, overall, the observed cupule modes appear independent of condition. Generally, we have found that there are no differences in abundances and types of scoria body cupules between sectors. However, cupules on the sides of scoria bodies are the most common.

Condition	S	T	BS	ST	BST	0	Total
P	7	1	1	0	0	5	14
F	6	3	0	3	1	2	15
G	12	0	0	1	0	2	15
E	1	0	0	1	0	1	3
Total	26	4	1	5	1	10	47

Table 18. Observation matrix listing intersections of side cupule and condition modes. Note the slight tendency of fewer cupules present in scoria bodies with lower grade condition mode. The values in this observation matrix to not deviate significantly from those in the contingency matrix ($p = 0.270$).

Puna Pau Scoria Bodies

To this point, I have reported only on the variation of coastal *pukao*. I now take some time to discuss the form and surface features of scoria bodies in the quarry at Puna Pau. Most scoria bodies in Puna Pau rest on their sides and are partially buried, thus complicating an examination of body dimensions. However, the scoria bodies of Puna Pau include a large amount of surface markings.

Eleven of the thirteen scoria bodies sampled (about 85%) include side striations, and most of these striations are horizontal. Specifically, eight (about 62%) have horizontal striations. Six (about 46%) have vertical striations, and only one has diagonal striations. Of the bodies with horizontal striations, half include both horizontal and vertical striations (about 31% of total). The majority of Puna Pau scoria bodies include side striations, and horizontal side striations are the most abundant.

Twelve of the thirteen scoria bodies sampled (about 92%) include cupules. Given that there is no distinction between top and bottom with the Puna Pau scoria bodies, we can only distinguish between cupules on the sides of the cylinder and those on the two roughly circular faces. Seven scoria bodies (about 54%) have cupules on the

two circular faces, and seven (about 54%) have side cupules. Of these, two (about 15% of total) include cupules on both the two roughly circular faces and the sides of the cylinder. Overall, the majority of Puna Pau scoria bodies include side cupules, and the side cupules are equally distributed by body face.

Other Sources of Variation

Additional variation in *pukao* and other cylindrical scoria bodies stems from the presence or absence of the following features:

- Petroglyphs
- Slabs Missing
- Basins
- Englert Numbers
- Western Text

The remaining discussion will focus on each of these dimensions in turn.

Petroglyphs

Linton Palmer (1870, 176) was the first visitor to Rapa Nui to report that fallen *pukao* were “all more or less marked by rude carvings of ships, birds, etc.” (Figure 47). Heyerdahl and Ferdon (1961, 237) also mention the presence of “incised crescent-shaped boats” on fallen *pukao*. Van Tilburg and Lee (1987, 142) have since documented many of the petroglyphs on *pukao* and other scoria bodies (Figure 48), and they hold that many (if not all) petroglyphs were added after *pukao* fell from *moai*. I define petroglyphs as any curved lines or collections of lines that do not form linear striations. I also distinguish Western text from petroglyphs. Most petroglyphs are less than a couple of centimeters deep.

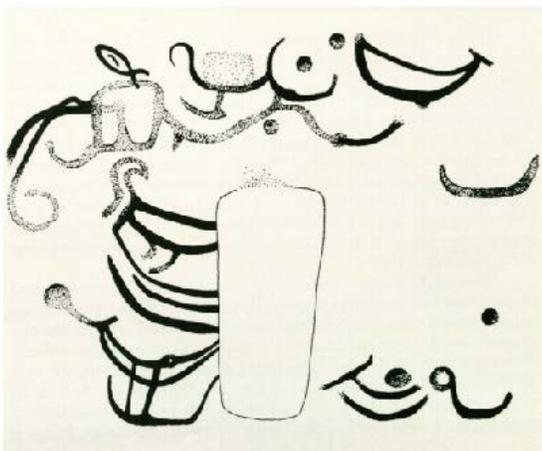
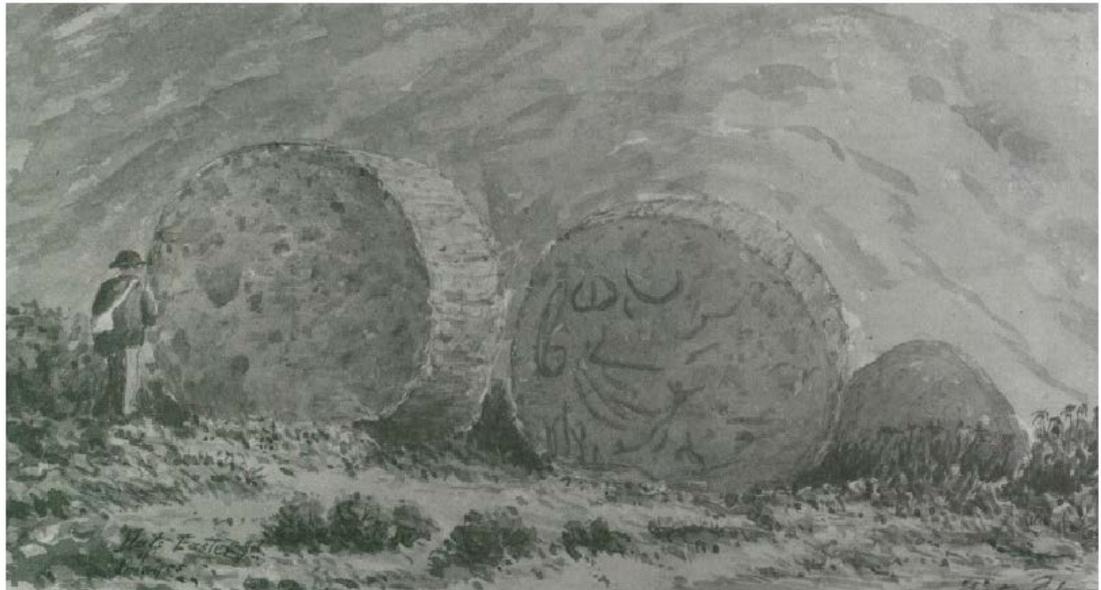


Figure 47. A watercolor from Linton Palmer's 1868 visit to the island (top, after Van Tilburg, 1992: 171) showing a few of the Puna Pau scoria bodies. The petroglyphs in the scoria body at center in Palmer's watercolor match those on a scoria body recorded by Georgia Lee (1992: 125) and the author (lower right). Note that this is scoria body 77 and that a notch was carved into the side of this body sometime between 1868 and 1992.

AHU ONE MAKIHI SITE 14-21 RED SCORIA FACIA														
AHU VINAPU II SITE 2-209 RED SCORIA FACIA AND PUKAO														
AHU AKAHANGA SITE 7-564 RED SCORIA FACIA AND PUKAO														
AHU VAIHU SITE 6-255 RED SCORIA PUKAO														
AHU HEKII RED SCORIA PUKAO														
PUNA PAU SITE 4-137 RED SCORIA PUKAO														

Figure 48. Various tracings of petroglyphs on red scoria *pukao*, Puna Pau scoria bodies, and red scoria *ahu* lentils, organized by location (after Van Tilburg and Lee, 1987: 142).

In their examination of petroglyphs, Van Tilburg and Lee document only those located at Puna Pau and five coastal *ahu* (Figure 48). I expand on this documentation by digitally tracing petroglyphs from *pukao* at five additional *ahu* (Hanga Poukura, Tarakiu, Ura Uranga te Mahina, Tongariki, and Te Pito Kura). Petroglyphs are less abundant at these five additional *ahu* than at the five noted by Van Tilburg and Lee, and *pukao* at Tu'u Tahī and Anakena do not include petroglyphs. Overall, 27 of the 50 coastal scoria bodies considered (54%) include petroglyphs and 12 of the 13 scoria bodies considered in Puna Pau (92%) include petroglyphs.

Comparing abundances of red scoria body petroglyphs by region, Puna Pau scoria bodies include the greatest abundance of petroglyphs (92%), while Sector III scoria include the lowest abundance of petroglyphs (40%). When we consider Puna Pau as Sector IV, we find that the spatial distribution of petroglyphs significantly deviates from expected values ($p = 0.0397$, Table 19). This deviation from expected values can be explained by the high abundance of petroglyphs in Sector IV. Jaussen

interprets the abundant petroglyphs in Puna Pau as the “proprietary marks (*rona*) of the owners,” but their age is unclear (Métraux 1940/1970, 303).

Sector	With Petroglyphs	Total	With Petroglyphs (%)
I	19	30	63
II	5	10	50
III	4	10	40
IV	12	13	92
Total	40	63	63

Table 19. Comparison of petroglyph presence on scoria bodies by sector. The spatial distribution of scoria bodies with petroglyphs in this sample significantly deviates from expected values (Fisher’s exact test; $p = 0.0397$).

Taking a closer look at the different types of petroglyphs, I classify them based simply on their form in order to avoid ascribing subjective meaning. Following this approach, petroglyphs may be isolated curved lines, collections of lines that create a closed form, or circles. The former is the most abundant, for every scoria body that includes petroglyphs includes isolated curved lines (Figure 49). This allows us to conclude that the spatial distribution of isolated curved line petroglyphs significantly deviates from expected values ($p = 0.0397$). Pointing to Figure 48, Van Tilburg and Lee (1987, 143) note the “high degree of conformity between and among the designs at all six sites,” but this spatial conformity in general form is evidently not reflected in abundances by sector.

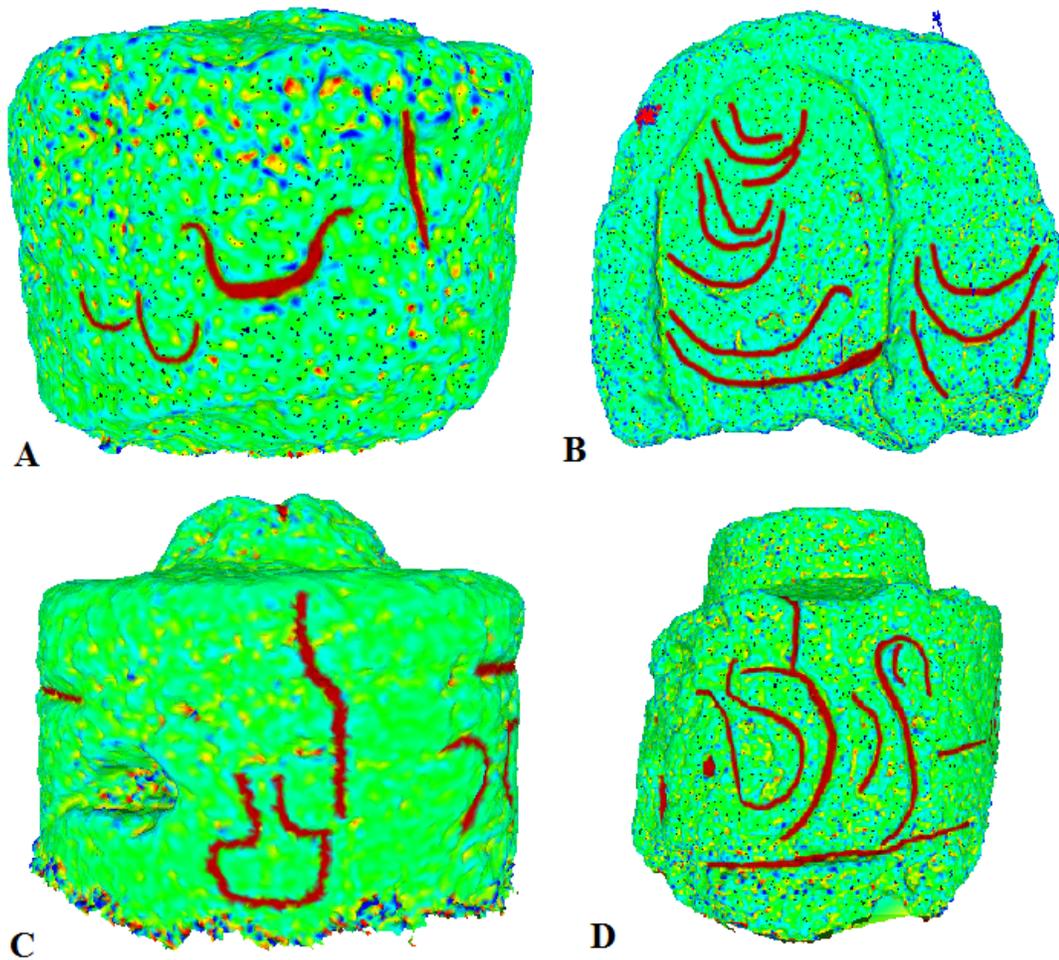


Figure 49. Various *pukao* with isolated curved line petroglyphs. (A) *Pukao* 17 from Tarakiu, (B) 19 from Vaihu, (C) 5 from Vinapu, and (D) 18 from Vaihu. Lee notes that “The majority of designs are simple canoe shapes” and speculates that their widespread distribution may be because they “marked a victory or conquest over another section of the island” (1992, 122/126). However, note the extensive variability in the form of curved line petroglyphs among those shown above.

Petroglyphs with curved lines that define closed forms also occur on scoria bodies, but they are restricted to Sectors I and IV (Table 20, Figure 50). This mode of petroglyph is most abundant in Puna Pau (about 62%) and the spatial distribution of this petroglyph mode deviates quite significantly from expected values ($p = 0.00038$).

Sector	With Closed Curved Forms	Total	With Closed Curved Forms (%)
I	4	30	13
II	0	10	0
III	0	10	0.
IV	8	13	61.54
Total	12	63	19.05

Table 20. Comparison of closed curved form petroglyph presence on scoria bodies by sector. The spatial distribution of scoria bodies with closed curved form petroglyphs in this sample significantly deviates from expected values (Fisher's exact test; $p = 0.00038$).

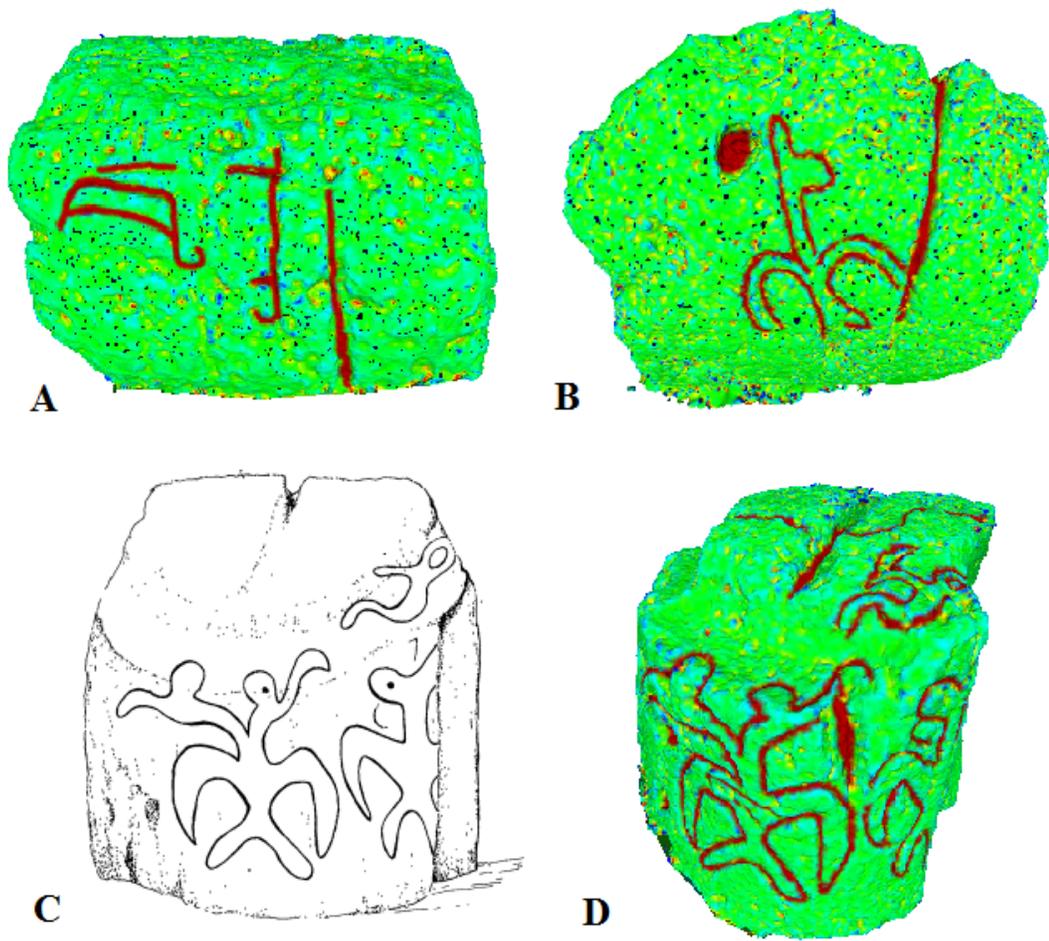


Figure 50. Various scoria bodies with closed curved form petroglyphs. (A) scoria body 80 from Puna Pau, (B) *pukao* 35 from Akahanga, (C) *pukao* 36 from Akahanga (after Van Tilburg and Lee, 1987: 145), and (D) *pukao* 36 from Akahanga. Van Tilburg and Lee refer to the forms from Akahanga as “birdman symbols” (1987, 143), but Lee later refers to that at bottom as a two-headed frigate bird (1992, 20).

Just like closed curved form petroglyphs, circle petroglyphs are restricted to Sectors I and IV (Figure 51). Three *pukao* in sector I include circles, and one scoria body in Puna Pau includes a circle. Based on Fisher's exact test the spatial distribution of this petroglyph mode does not deviate significantly from expected values ($p = 0.8101$).

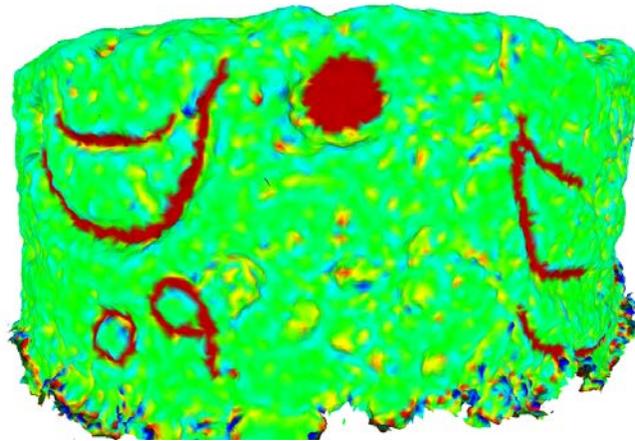


Figure 51. *Pukao* 4 from Vinapu with isolated curved lines, a cupule, and circles at the lower left.

Finally, in four *pukao*, relatively large pairs of side cupules located near the base that are horizontally level may be interpreted as a fourth type of petroglyph. Van Tilburg (1992, 200) specifically refers to *pukao* 41 at Tu'u Tahi (Figure 52), which she claims has been "recarved with Make Make eyes." According to Heyerdahl and Ferdon (1961, 41), Make Make is "the principal Easter Island god." Distinctly carved pairs of cupules such as those on the *pukao* at Tu'u Tahi also appear on three other *pukao* at different locations (Figure 53).

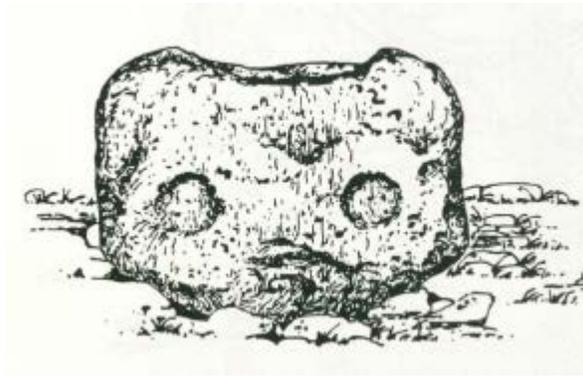


Figure 52. Drawing by P. Cristián Arévalo of *pukao* 41 at Tu'u Tahi with horizontally aligned side cupules (after Van Tilburg, 1992: 200).

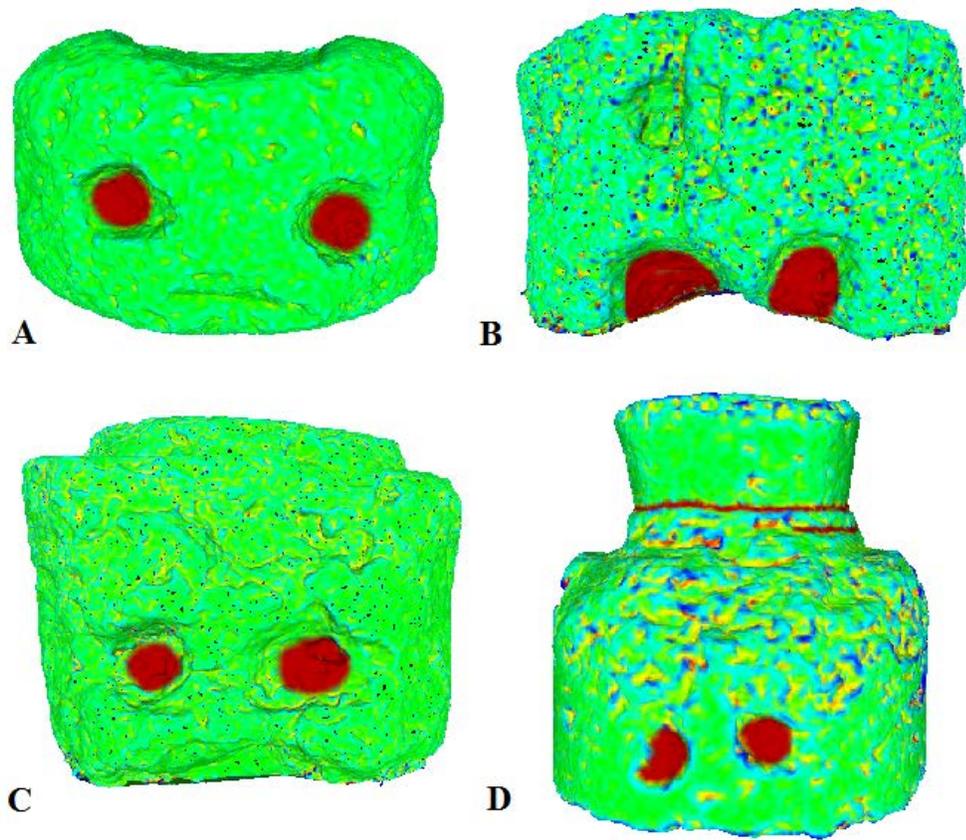


Figure 53. The four *pukao* that include horizontally-aligned pairs of side cupules near their bases. (A) *Pukao* 41 from Tu'u Tahi, (B) 23 from Vaihu, (C) 51 from Tongariki, and (D) 57 from Hekii.

Slabs Missing

Along the Rapa Nui coastline, there exist five *pukao* with slabs of scoria removed along the upper edge of the body (Figure 54). At least some of these features were present during Cook's visit to the island in 1774, for he notes that "In some, the upper corner of the cylinder was taken off in sort of a concave quarter-round; but in others the cylinder was entire" (1777/2005, 160). During his 1868 visit to the island, Palmer (1870, 179) also notes notches in a scoria body at Akahanga: "the top was flat, and cut away on each side, so as to make a step or shelf." This description matches the current appearance of *pukao* 34 at Akahanga. Regarding this *pukao*, Palmer (1870, 179) continues: "On it I found two skulls, very much perished, which, from the dentition, I judged to be those of youths of twelve or fourteen years old." Métraux (1940/71, 302) later notes Palmer's association between death and the *pukao* with slabs missing and asserts that such *pukao* "seem to have been supports for a wooden frame on which corpses were exposed." Katherine Routledge (1919/1998, 229) holds a similar view: There exist pieces of *pukao* and *moai* at an *ahu* along the southern coast that were "specially used for exposing 'fish men,'" otherwise referred to as "corpses of slain men." Historic sources suggest that the relatively few fallen *pukao* with slabs missing served a purpose in funerary rituals, but it is also possible that people removed such slabs for other purposes (e.g. building materials or *ahu* lentils).



Figure 54. Four of the *pukao* that have large slabs missing from the upper body edges. (A) *Pukao* 14 from Hanga Poukura, (B) 34 from Akahanga, (C) 38 from Akahanga, and (D) 49 from Tongariki (photos by author, 2014). The fifth *pukao* with a slab missing is located at Hekii.

Several of the Puna Pau scoria bodies also have slabs missing, but these slabs tend to be more irregular in form. For example, recall the rectangular notch carved into scoria body 77 following the creation of Palmer’s watercolor depiction (Figure 47). Scoria body 80 at Puna Pau includes a notch similar in size, shape, and placement, and scoria body 86 (Figure 55) has a large slab missing from its base, which leaves a significant concave hollow beneath it. This hollow was quite likely present during Métraux’s visit to the island: During a rainy day at Puna Pau, he “took refuge inside one of these cylinders that had been converted into a shelter” (Métraux 1957, 201). Given that this scoria body did not have this concave hollow during Palmer’s visit, we

can date the removal of this slab to sometime between 1868 and 1934. A few irregular slabs are missing from Puna Pau scoria bodies for unknown reasons.



Figure 55. Scoria body 86 from Puna Pau in upper photo at right with concave hollow missing (photo by author, 2014). In Linton Palmer's 1868 watercolor (bottom, after Van Tilburg, 1992: 171), these three scoria bodies are viewed from the opposite direction, so the scoria body with the current hollow is at left in the watercolor. Overall, the current concave hollow was created sometime between 1868 and 1934.

Basins

Two *pukao* located along the coastline have large carved basins with an oblong cross section (Figure 56). Heyerdahl and Ferdon note the basin in the *pukao* at Vinapu

and conducted a shallow excavation surrounding it (Figure 57). They it to be a “topknot resting upside down” (Heyerdahl and Ferdon 1961, 119), as do I, but did not excavate beneath it for verification. When Heyerdahl and Ferdon (1961, 119) observed this scoria body, “The concavity was partially filled with earth, which we removed to disclose two human deciduous molar teeth lying on its bottom.” They also note that “About two-thirds of the distance from the seaward end was found an elongated ovoid cobble which Martín Rapu thought may have been a head rest for a cadaver” (Heyerdahl and Ferdon 1961, 119). These observations lead them to speculate that “The concavity may have been used as a form of drying platform” (Heyerdahl and Ferdon 1961, 119). However, it is just as likely that the two red scoria bodies with basins carved were used to collect rainwater. Métraux (1957, 66) notes the use of carved stone basins called *taheta*: These “holes cut artificially in the rocks were – if the natives of our own day are to be believed – little reservoirs that served in days gone by to catch rainwater.”



Figure 56. The two *pukao* located along the southern coast with basins dug: *Pukao* 4 from Vinapu (top) and *pukao* 48 from One Makihi (bottom, photos by author, 2014).



Figure 57. Shallow excavation conducted by the Norwegian Archaeological Expedition in 1955 around the base of *pukao* 4 (after Heyerdahl and Ferdon, 1961: Appendix).

In addition to the two bodies with oblong basins, there are three with notable circular depressions of lesser volume in the center of the side of the *pukao* body that currently faces upward (Figure 58). Georg Forster noted a scoria body during his 1774 visit to the island at a poorly defined location that “had a hole on each side, as if it had been made round by turning” (Kahn 1968, 325). No subsequent visitor makes note of such holes. I witnessed no bodies with holes on both sides, but the three in Figure 58 may have holes on the face on which the body currently rests.

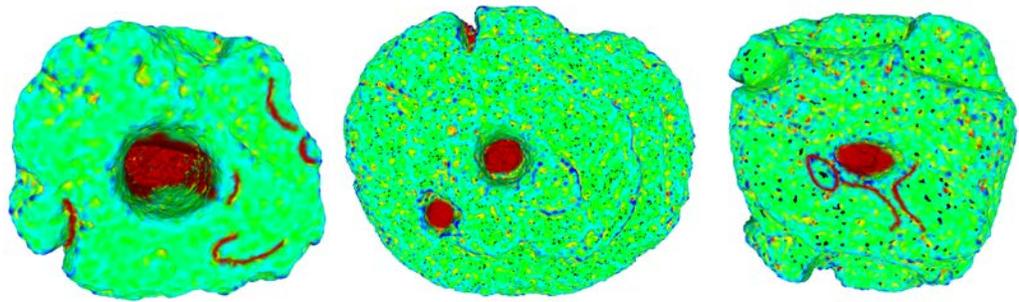


Figure 58. Top views of three *pukao* with notable circular holes in the center of the upward face. *Pukao* 14 is from Hanga Poukura (left), *pukao* 17 is from Tarakiu, and the *pukao* 34 is from Akahanga. The former *pukao* rests on its top, while the latter two rest on their bases.

Historic sources reveal a final past embellishment of *pukao* that appears to have left no remaining trace: Piles of white stones atop *pukao*. These piles may or may not be related to the presence of cupules on the tops of some *pukao*. Based on his 1722 visit to the island, Jacob Roggeveen provides the first reference to bodies of some white material resting atop *moai*: “They have on the head a basket heaped up with flints painted white deposited in it” (Ruiz-Tagle 2005, 32). Given that the *pukao* that we see today are not baskets, the editor notes that “Roggeveen’s description of the statues seems to show that he never got close to one of them, but saw them only from a distance of some hundreds of yards” (Ruiz-Tagle 2005, 32). However, it is possible that both organic baskets and red scoria *pukao* previously adorned *moai*. Also note that the white pebbles that Roggeveen notes are not entirely fictional, for Spanish visitors noted something similar forty eight years after Roggeveen’s visit. Specifically, Felipe González de Haedo notes that “there is a small concavity on the upper surface of the [head-dress] in which they place the bones of their dead, from which it may be inferred that they serve at once for idols and funeral pyres” (Ruiz-Tagle 2005, 57). However, Métraux (1940/1971, 300) and Heyerdahl and Ferdon (1961, 110) believe that the

Spanish mistook coral fragments atop *pukao* for bone. In excavations of Vinapu, the Norwegian Archaeological Expedition came across “many small, smooth, beach pebbles of coral which varied from about 0.5 to 15 cm. in diameter. Juan Chavez said that he had heard that in earlier times people threw these on the tops of the topknots and that many were nearly covered with them” (Heyerdahl and Ferdon 1961, 110). The only other reference to white stones is one that Routledge (1919/1998, 199) briefly makes: “[The *pukao*] are said by the present inhabitants to have been kept in place by being wedged with white stones.” Overall, white stones involved in *pukao* adornment offer tantalizing glimpses into the past but evidently left very little trace on the physical form of the existing *pukao* with the possible exception of a couple of the holes noted in Figure 58.

Englert Numbers

Painted numbers constitute some of the most recently added variation among scoria bodies (Figure 59). Father Sebastian Englert, a Capuchin Franciscan friar who lived on Rapa Nui from 1935 until his death in 1969, applied these numbers to scoria bodies, *moai*, and various other archaeological features spread across the island. Though an eyesore, these numbers provide a diagnostic feature for scoria body identification. Of the scoria bodies considered, a total of 27 of 66 (about 41%) include Englert numbers. Of these, 22 of the 53 bodies observed along the coast (about 42%) and 5 of the 13 scoria bodies observed in Puna Pau (about 38%) include Englert numbers.



Figure 59. Two scoria bodies with clearly-marked Englert numbers: *Pukao* 65 from Anakena (left) and scoria body 88 from Puna Pau (right, photos by author, 2014).

Western Text Engravings

Aside from Englert numbers, a few scoria bodies include engraved Western text (Figure 60). Western text engravings are most abundant in Puna Pau, for 5 of the 13 Puna Pau scoria bodies (about 38%) include such engravings, while only two *pukao* along the coastline (one at Vinapu and the other at Akahanga) include such engravings. The origin of these engravings is unknown, but it is understandable to find the most abundant graffiti in Puna Pau given its close proximity to Hanga Roa, which is the only current residential area on Rapa Nui.

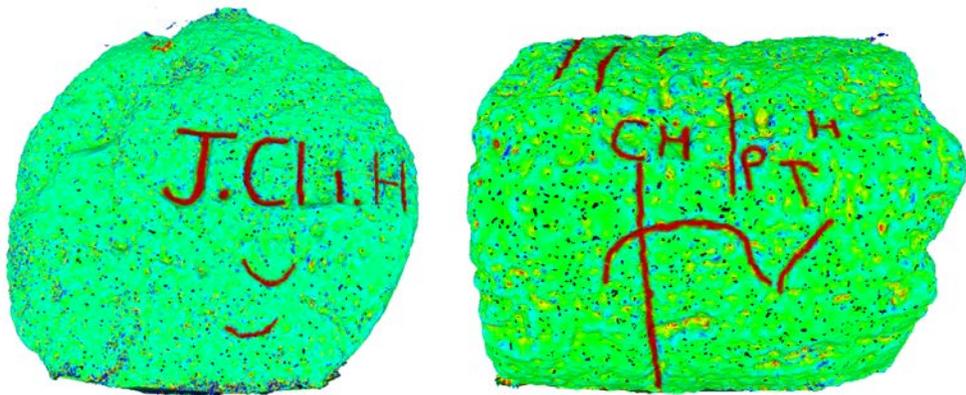


Figure 60. Two scoria bodies at Puna Pau (77 at left and 80 at right) with engraved Western text.

Conclusion

Implications of *Pukao* Dimensions for Transport

Volume

Though insignificant ($r^2 = 0.344$), the slight positive correlation between *pukao* volume and distance from quarry (Figure 31) indicates that *pukao* distant to the quarry represent greater investments of energy than those located nearer to the quarry. A greater number of volume measurements of higher precision are needed in order to better test the strength of this correlation. If this correlation remains significant, then it may be explained by future research. It may be the case that the Rapanui simply moved larger scoria bodies further across the island in order to adorn the heads of possibly larger *moai* that are located closer to the main statue quarry (recall that Puna Pau and Rano Raraku are located on nearly opposite ends of Rapa Nui, Figure 1).

Base Indentation

The presence of base indentations on all well-preserved *pukao* with bases exposed and the associated scarcity of base striations have implications regarding transport. This set of observations suggests that the Rapanui did not slide *pukao* onto the top of *moai* for three reasons. First, it is difficult to carve a properly-oriented base indentation to match the top dimensions of a *moai* when the *pukao* is resting on its base prior to sliding. Second, shallow base indentations made in the relatively friable red scoria of the *pukao* would likely be erased by friction associated with sliding a *pukao* over much distance. Finally, if the Rapanui slid *pukao* into place, then we would expect some preserved wear deformation in the base of *pukao* from friction (refer to Table 3).

No amount of refinishing could erase scratches due to sliding on the base once the *pukao* is placed atop the *moai* and the face between the two becomes sealed. The mere presence of the base indentation free of striations negates the hypotheses involving sliding: including the Tower Hypothesis (attributed to Vincent Lee, Figure 11) and the Wooden Ramp Hypothesis (attributed to Pavel Pavel, Figure 13).

Aside from not explaining observations from the archaeological record, the Wooden Ramp Hypothesis loses its physical feasibility when applied to large *pukao* masses and *moai* heights. Pavel Pavel's (1995, 71) experiment involved raising a 900 kilogram *pukao* to the top of a 3 meter *moai* using two parallel beams of wood. Though hardwood from the relatively small *Sophora toromiro* tree was available in the past on Rapa Nui (Horrocks et al. 2012), the wood involved in the Wooden Ramp Hypothesis most likely would have been collected from the now-extinct palm *Pashalococos disperta*, which was likely closely related to *Jubaea chilensis* (Gurley and Liller 1997, 82). Palm trunks are a poor material for bearing loads because palms are actually large grasses with spongy interiors. *Jubaea chilensis* reaches an average height of 20 meters after 60 years of growth, and, on its side, the trunk can support about 6 tons (Gurley and Liller 1997, 83). Despite this strength estimate, relatively massive *pukao* (upwards of 10 metric tons) applying a torque with a lever arm of up to 10 meters would very likely cause a wooden ramp made of two unsupported trunks of *Jubaea chilensis* to yield.

Physical Form

Despite the fact that most *pukao* share a cylindrical form with an oblong horizontal cross section, the physical form of *pukao* does not appear to hold immediate implications regarding transport. For example, the oblong section shared by all *pukao*

potentially reflects an aspect of the transport method that involved rolling up a ramp. Rolling can be achieved with oblong cross sections, but it is important to note that oblong sections are not incompatible with any other proposed transport methods. While the presence of *pukao* with conical forms (e.g. Figure 38) argues against any hypothesis involving rolling up a ramp, it is possible that prehistoric Rapanui carved *pukao* to their current form only after placing the *pukao* atop *moai*. The possibility of finishing *pukao* carving at the top of *moai* may be supported by the fact that the best preserved *pukao* at Anakena have exceptionally smooth sides with few to no surface markings: I assume that these smooth *pukao* surfaces were not refinished during the recent reconstruction of Ahu Nau Nau at Anakena.

Carved top cylinders display a high degree of variability throughout the island, with significant differences between the northern and southern coasts (Figure 41). If the presence of top cylinders holds any functional value, then it must be a value that leaves top cylinder form quite unconstrained.

Surface Variation

The surface variation of *pukao* may hold implications regarding transport, but they are difficult to establish when we consider that (a) the Rapanui may have refinished *pukao* after they reached the top of *moai* and (b) the existing surface variation may be a product of activity following the toppling of *pukao*. Abundant horizontal striations found along the side of scoria body 71 near Anakena (Figures 9, 30, and 45) can be interpreted as scratches associated with sliding while rolling. The abundance of horizontal striations on many of the Puna Pau scoria bodies can be interpreted similarly. This observation and interpretation aligns with the established reasoning that the

Rapanui rolled relatively large bodies of scoria across the island for use at coastal *ahu*. It is important to note that the absence of abundant horizontal striations on the sides of *pukao* does not rule out a transport hypothesis involving rolling up a ramp. First, sliding may not have taken place while rolling a *pukao* up a ramp. Second, striations from sliding up a ramp may have been erased when the Rapanui refinished *pukao* at the top of a ramp.

The horizontal and abundant vertical striations found on *pukao* may support William Mulloy's Simultaneous Set Up Hypothesis (1970, 16, Figure 12). With this interpretation, striations represent notches used to help affix *pukao* to *moai* during the raising of the *moai*. However, few *pukao* include both horizontal and vertical striations. Vertical striations are rarely wide enough to act as notches for bound beams (although they are wide enough for rope), and they rarely extend along an entire face of the *pukao*.

The possibility of functional value associated with side cupules is similarly inconclusive. Cupules most often found on the curved sides of *pukao* may have aided in gaining traction while rolling *pukao* up a ramp, but side cupules may again represent late additions that came following the toppling of *pukao*. For example, Lee (1992, 124) speculates that cupule carving in *pukao* and *moai* is "a case of trying to extract the *mana* from them, or to release, and thus destroy, the *mana* inherent in them." Better information on the timing of modifications to *pukao* is required to discern the sequence of events inherent in their manufacture.

The Modified Ramp Hypothesis

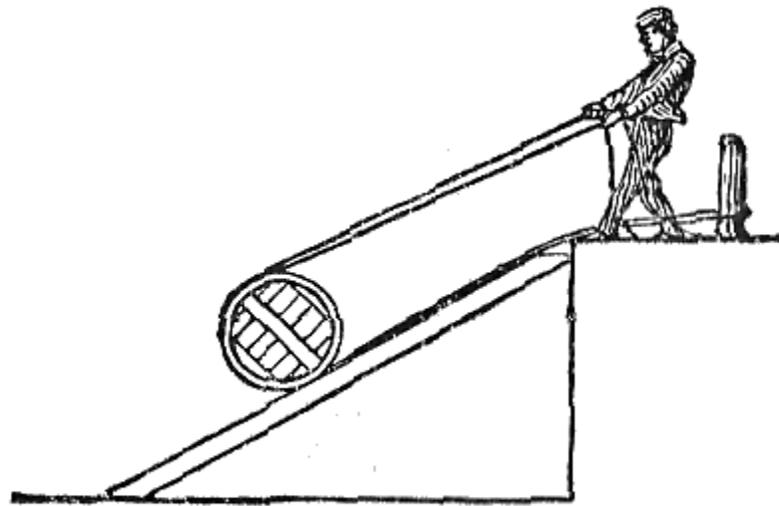
Upon first glance, most of the variable *pukao* dimensions appear to have inconclusive associations with transport function. Only the presence of base

indentations helps us confidently narrow down the hypotheses to either those involving rolling up a ramp or simultaneous *moai* and *pukao* set up. As mentioned earlier, Lipo et al. (2013) used archaeological observations and experimental verification to firmly establish ‘walking’ as the prehistoric means of *moai* transport. This work allows us to make further inference regarding *pukao* transport by significantly diminishing the viability of Mulloy’s hypothesis involving simultaneous set up of *moai* and *pukao* from a horizontal position. Specifically, this leaves us with some form of the Ramp Hypothesis for the majority of *pukao* transport. What follows is an exploration of the physical feasibility of the Ramp Hypothesis and a summary of how a modified version of this hypothesis (the Modified Ramp Hypothesis) successfully explains observations of the archaeological record. In this exploration, I make assumptions that establish the minimum physical requirements for the Modified Ramp Hypothesis.

The first question that arises when considering any version of the Ramp Hypothesis is which direction does the ramp extend. Given that seawalls of *ahu* often drop precipitously to the adjacent intertidal zone and that *moai* are aligned along the length of *ahu* parallel to the coastline, it would be most feasible to construct a ramp for *pukao* transport on the inland side of the *ahu*. Similarly, I assume that the Rapanui used a straight ramp coming off of the front of *moai* instead of a zig-zag situation stacked in front of a *moai*, for the latter situation limits the number of people that can be involved in applying a force for transport.

I consider two possible techniques of rolling a *pukao* up a ramp: pulling from above and/or levering from below. Pulling from above can be accomplished by using rope in a parbuckle setup (Figure 61). 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. Note that either stakes at the top of the ramp or the top of the *moai* can serve as the anchor in the parbuckle setup. Rope was certainly available to the Rapanui, for ethnohistoric accounts document the local tradition of producing cordage and rope (*hau*) from the bark of *Triumfetta semitriloba*, a woody shrub that still grows on the island (Métraux 1940/1970, 210). Additionally, levering a *pukao* from below can be accomplished by using relatively small branches from trees, such as *Sophora toromiro*, that previously grew on the island (Horrocks et al. 2012).



Parbuckle.

Figure 61. The configuration of a parbuckle. Note the parbuckle anchor behind the person and that such parbuckles were once commonly used in preindustrial Europe for transporting barrels up and down inclines. Source: “Parbuckle – Chambers’ Twentieth Century Dictionary of the English Language.” *Wikipedia: The Free Encyclopedia*. Wikipedia Foundation, Inc. 17 Jan. 2012. Web. 20 May 2015.

Physics Derivation: Pushing through Levering

We would like to find a simplified equation that relates the angle of incline of the ramp to the force due to people applied to the upper portion of a lever in contact with a *pukao*, as shown in Figure 62.

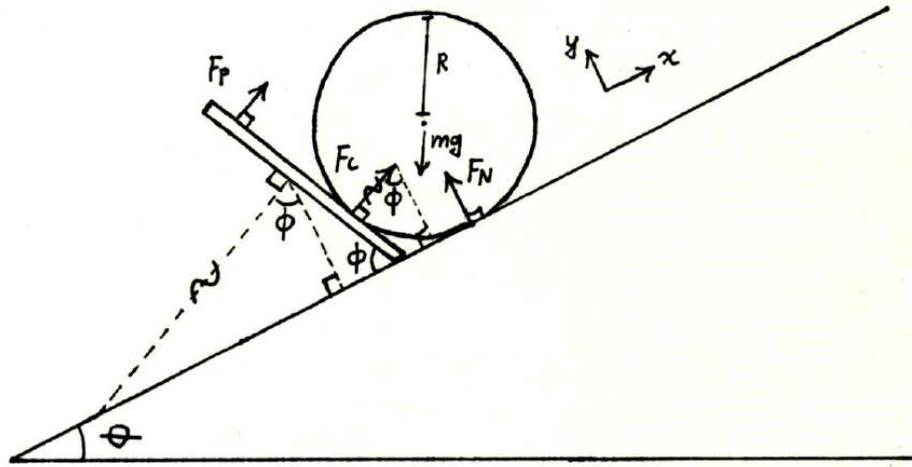


Figure 62. Forces involved in levering a *pukao* of radius R up a ramp, where θ gives the angle of incline of the ramp. The force on the *pukao* due to gravity acts downward at the center of mass of the *pukao* and is given by mg , where m is the mass of the *pukao* and g is the acceleration due to gravity. The normal force due to the ramp acts perpendicular to the ramp and is designated by F_N . A person exerts a force F_P on the top of the lever, and this force is communicated through force F_c where the lever and *pukao* touch. The angle ϕ here represents the angle formed by a line normal to the ramp surface and a line normal to the lever. Note that we know that the lever case of static equilibrium is stable only if $\phi \geq \theta$. The reference for this situation is modified for convenience such that x is parallel to the inclined ramp surface.

We begin by considering the sum of forces in the x - and y -directions when the *pukao* is in a state of static equilibrium. Note that the x and y components of the force acting between the lever and *pukao* at the point of contact are given by F_{cx} and F_{cy} , respectively.

$$\Sigma F_x = F_{cx} - mg \sin \theta = 0 \quad (1)$$

$$\Sigma F_y = F_N + F_{cy} - mg \cos \theta = 0 \quad (2)$$

Given how we previously defined F_c and ϕ , we can relate F_{cx} and F_{cy} to F_c through the following two equations.

$$F_{cx} = F_c \sin\phi \quad (3)$$

$$F_{cy} = F_c \cos\phi \quad (4)$$

By substituting equation (3) into equation (1), we come to equation (5), and by substituting equation (4) into equation (2), we come to equation (6), as seen below.

$$F_c \sin\phi - mg \sin\theta = 0 \quad (5)$$

$$F_N + F_c \cos\phi - mg \cos\theta = 0 \quad (6)$$

Given that the normal force is of little interest to us, we will continue by using only equation (5). In order to find F_c in terms of F_p , we must now consider the sum of torques acting on the lever, as outlined below in Figure 63.

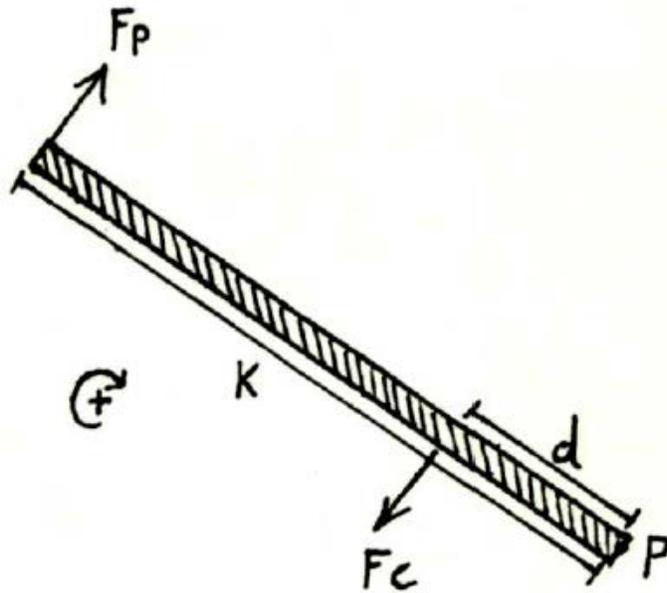


Figure 63. Torques acting on the lever as it pivots around point P. Here, the force F_c pushing back from the *pukao* acts at a distance d from the pivot point. Meanwhile, the force F_P acts in the positive direction at a distance k from the pivot point.

Given that the situation in Figure 63 is in static equilibrium, we can express the torques in the system through equation (7).

$$\Sigma\tau = 0 = F_P k - F_c d \quad (7)$$

Solving equation (7) for F_c , we come to equation (8).

$$F_c = F_P \left(\frac{k}{d} \right) \quad (8)$$

Substituting equation (8) into equation (5), we come to equation (9).

$$F_P \left(\frac{k}{d} \right) \sin\phi - mg \sin\theta = 0 \quad (9)$$

Given equation (9), we would now like to get d and ϕ in terms of known variables. Starting with d , consider Figure 64 below.

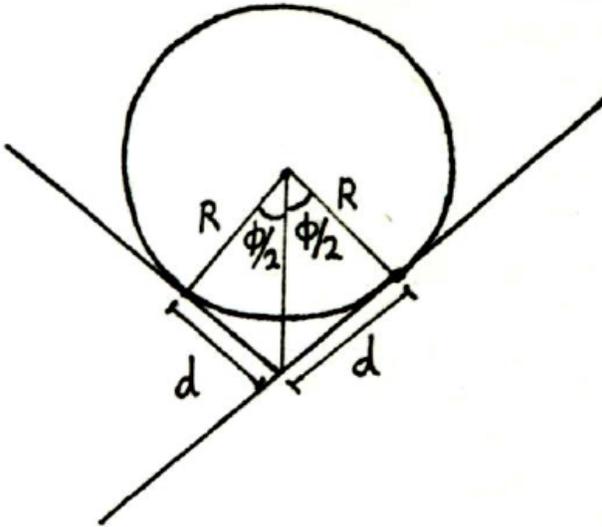


Figure 64. An analysis of the distance d and how it relates to ϕ . Two lines tangent to a circle intersect at a distance d from their individual points of tangency. Because the radius of the circle (R) is constant, two triangles can be drawn with a shared hypotenuse. Thus, we have two identical triangles and know that their hypotenuse must bisect the angle ϕ as shown.

By examining one of the triangles formed Figure 64, we find equation (10).

$$\frac{d}{R} = \tan\left(\frac{\phi}{2}\right) \quad (10)$$

Solving equation (10) for d , we come to equation (11).

$$d = R \tan\left(\frac{\phi}{2}\right) \quad (11)$$

We now substitute equation (11) for d into the leftmost term in equation (9) and come to equation (12) by expanding the tangent term.

$$F_p \left(\frac{k}{d} \right) \sin \phi = F_p \frac{k \sin \phi}{R \left(\frac{\sin(\frac{\phi}{2})}{\cos(\frac{\phi}{2})} \right)} \quad (12)$$

Equation (12) can be rewritten as follows using a trigonometric identity for sine.

$$F_p \frac{k(2 \sin(\frac{\phi}{2}) \cos(\frac{\phi}{2}))}{R \left(\frac{\sin(\frac{\phi}{2})}{\cos(\frac{\phi}{2})} \right)}$$

The above term simplifies to the following.

$$F_p \frac{k 2 \cos^2(\frac{\phi}{2})}{R}$$

Adding the above modified term back into equation (9), we come to equation (13).

$$F_p \frac{k 2 \cos^2(\frac{\phi}{2})}{R} - mg \sin \theta = 0 \quad (13)$$

We find the equation (14) below by solving equation (13) for F_p .

$$F_p = \frac{R mg \sin \theta}{2k \cos^2(\frac{\phi}{2})} \quad (14)$$

We now consider the upper limit of F_P when $\phi = \theta$, as shown below in equation (15). This situation corresponds to an overall vertical lever force that acts directly against the full force due to gravity of the *pukao*.

$$F_{pmax} = \frac{Rmg\sin\theta}{2k\cos^2\left(\frac{\theta}{2}\right)} \quad (15)$$

The right term in equation (15) can be expanded to the following using a trigonometric identity for sine.

$$\frac{Rmg(2\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{\theta}{2}\right))}{2k\cos^2\left(\frac{\theta}{2}\right)}$$

By simplifying the above term in equation (15), we come to equation (16).

$$F_{pmax} = \left(\frac{mgR}{k}\right)\tan\left(\frac{\theta}{2}\right) \quad (16)$$

In this equation, the variables m and R are fixed for a given *pukao*, the length of the lever k can be approximated by considering a reasonable height of a person. Thus, we have found an expression that relates the angle of incline of a ramp θ to the maximum force that people exert on the *pukao* through a lever.

Physics Derivation: Pulling with Rope

We would like to find a simplified equation that relates the angle of incline of the ramp to the force due to people applied to the top of the *pukao* through pulling with rope through parbuckling, as depicted below in Figure 65. In this situation, we assume that the applied force is roughly parallel to the ramp surface. The latter assumption is

reasonable given the height of *pukao* on its side, the length of the ramp, and the height of a person.

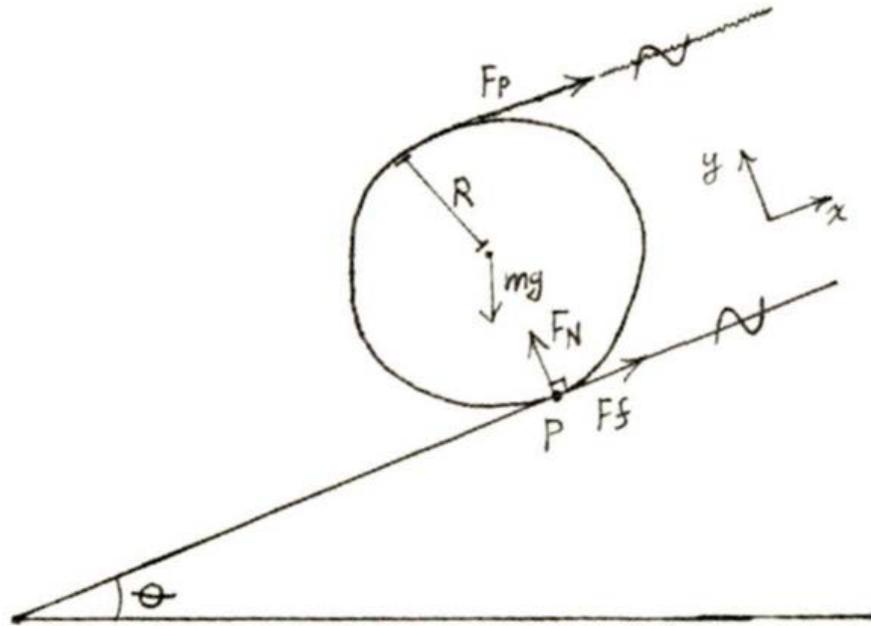


Figure 65. Forces involved in pulling a *pukao* of radius R up a ramp, where θ gives the angle of incline of the ramp. The force on the *pukao* due to gravity acts downward at the center of mass of the *pukao* and is given by mg , where m is the mass of the *pukao* and g is the acceleration due to gravity. The normal force due to the ramp acts perpendicular to the ramp and is designated by F_N . A person exerts a force F_P on the rope, and this force is communicated to the top of the *pukao*. A force of friction designated by F_f acts as shown in order to prevent the *pukao* from slipping. The *pukao* pivots as it rolls around the point P . The reference for this situation is modified for convenience such that x is parallel to the inclined ramp surface.

Given that the situation in Figure 65 is in static equilibrium, we can choose to examine both the sum of forces acting in the x - and y -directions and the sum of torques. Given that the friction force is difficult to work with, we eliminate it by considering the

sum of torques acting on the *pukao* around the pivot point P. This leads us to equation (17).

$$\Sigma\tau = 0 = 2RF_p - Rmg\sin\theta \quad (17)$$

Solving equation (17) in terms of F_p , we come to equation (18).

$$F_p = \left(\frac{mg}{2}\right)\sin\theta \quad (18)$$

In equation 18, we have found an equation that relates the angle of incline of the ramp to the force due to people applied to the top of the *pukao* through pulling with rope. In this relatively simple situation, the applied force needed to move the *pukao* is only dependent on the mass of the *pukao* and the angle of incline.

Implications of Transport Equations

The derived transport equations (summarized in Figure 66) help describe *pukao* transport. Below, I explore the implications of these equations for *pukao* transport by considering measurements of *pukao*, *moai*, and *ahu* at four different locations on Rapa Nui (Table 21). Generally, Newtonian physics and human strength estimates verify that *pukao* transport by rolling up a ramp is physically feasible.

<p>Pushing</p> $F_{pmax} = \left(\frac{mgR}{k}\right)\tan\left(\frac{\theta}{2}\right)$	<p>Pulling</p> $F_p = \left(\frac{mg}{2}\right)\sin\theta$
--	---

Figure 66. Equation giving the force required to move a *pukao* up a ramp by pushing with a lever (left, equation 16) or by pulling with a parbuckle (right, equation 18). In both equations, the F term gives the force required to move the *pukao*, m gives the mass of the *pukao*, g stands for the acceleration due to gravity, and θ gives the ramp angle of incline. In the pushing/levering equation at left, R refers to the radius of the *pukao*, and k refers to the length of the lever.

<i>ahu</i>	h (m)	<i>Pukao</i> Number	m (kg)	R (m)	<i>Pukao</i> h (m)	k (m)
Vaihu	8	23	$6,383 \pm 2,920$	1.2	1.2	1.4
Ura Uranga te Mahina	8	29	$3,541 \pm 726$	1.0	1.1	1.4
Akahanga	8	38	$4,170 \pm 603$	0.7	1.0	1.4
Te Pito Kura	10	73	11,500	1.3	1.8	1.4

Table 21. Estimated absolute scale values for dimensions of *pukao*, *moai*, and *ahu* at four locations used in sample physical calculations graphs. True to the equations derived in the Appendix, 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 1.4 meters for k is reasonable when assuming that human height ranges between 1.5 and 1.6 meters. Measurements from Te Pito Kura are taken from Heyerdahl and Ferdon, 1961. Other measurements come from those taken in the field by teams under Hunt and Lipo, but *pukao* mass estimates come from the models that I generated in this project.

Graphing the force required to pull or lever *pukao* up a ramp with variable angle of incline at each location by considering the equations in Figure 66 and the values in Table 21 produces Figure 67. This figure, combined with basic human strength estimates, supports the conclusion that relatively small numbers of people can transport a *pukao* up a ramp with angles of incline between 5 and 20 degrees. In this assessment,

I rely on Snook and Ciriello's (1991) comprehensive tables of human strength measurements that are frequently used in occupational safety planning. Though conservative (strength estimates are intended to avoid long term lower back pain), estimates for pushing and pulling assume that some portion of the population should be capable of pulling or pushing a mass of about 70 kg (about 686 N).

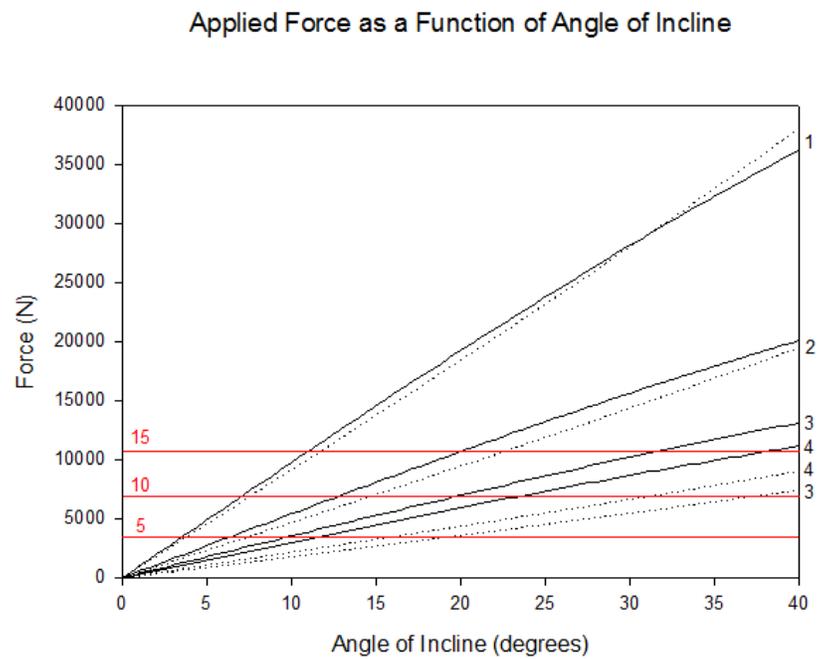


Figure 67. Applied force required to move *pukao* up ramps with variable angles of incline at four different *ahu* (1 = Te Pito Kura, 2 = Vaihu, 3 = Akahanga, and 4 = Ura Uranga te Mahina). Solid black lines represent force required with only pulling, and dashed lines represent force required with only pushing. When we consider a human strength estimate of 70 kg (686 N) per person, we can draw the three horizontal red lines above, which approximate the forces that can be applied by 5, 10, and 15 individuals.

Generally, the largest *pukao* (1, that at Te Pito Kura) requires the greatest force to roll at any given angle of incline. The *pukao* at Vaihu (2) requires an intermediate applied force, while those at Akahanga (3) and Ura Uranga te Mahina (4) require the

lowest applied force. Note that pushing through levering becomes more efficient than pulling when the radius and mass of the *pukao* are sufficiently low. In the case of Akahanga, the relatively small radius of the *pukao* enables it to be levered with a lower applied force than the less massive *pukao* at Ura Uranga te Mahina. However, only a limited number of people can lever behind a *pukao* (due to crowding), while many more can parbuckle from above. Indeed, an advantage of pulling up a straight ramp is that it maximizes the number of people that can apply a force. In Figure 67, the x-coordinate of the intersection of the red and black lines give estimates of angles of incline possible with different numbers of people at different locations. For example, at Vaihu (2), pulling groups ranging in size between 5 and 10 individuals are capable of pulling the *pukao* up a ramp of angle of incline between about 6 and 13 degrees.

William Mulloy acknowledges the possibility of such transport but objects that ramps (specifically at Te Pito Kura) would need to be “several hundred metres long – a seemingly prohibitive amount of construction” (1970, 15). However, we find that ramps several hundred meters long are not needed at any location when we plot force required to move a *pukao* against the length of the ramp (Figure 68). Even at Te Pito Kura, just ten people pulling the *pukao* can do so with a ramp length of less than one hundred meters (Figure 68).

Applied Force as a Function of Ramp Length

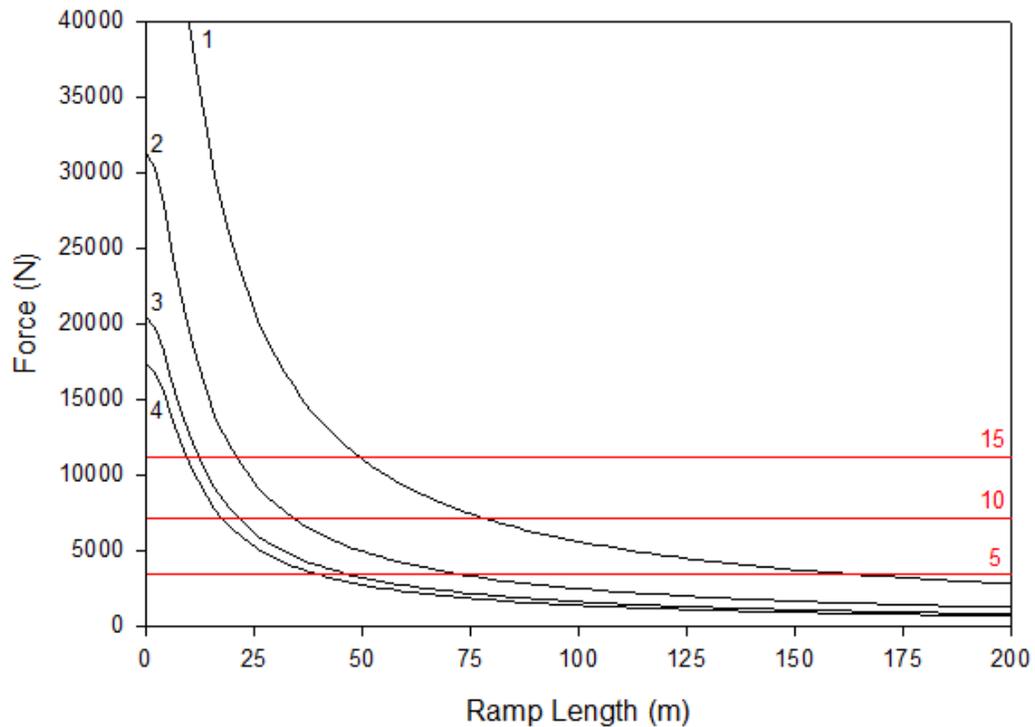


Figure 68. Applied force required to pull *pukao* up ramps with variable angles of incline at four different numbered *ahu* (1 = Te Pito Kura, 2 = Vaihu, 3 = Akahanga, and 4 = Ura Uranga te Mahina). Solid lines represent force required with only pulling. When we consider a human strength estimate of 70 kg (686 N) per person, we can draw the three horizontal red lines above, which approximate the forces that can be applied by 5, 10, and 15 individuals.

Figure 68 shows that 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). As in Figure 67, when we consider a human strength estimate of 70 kg (686 N) per person, we can draw the three horizontal red lines above, which approximate the forces that can be applied by 5, 10, and 15 individuals. Thus, the x-coordinate of the intersection of the red and black lines again give estimates of

ramp lengths possible with different numbers of people at different locations. For example, at Vaihu (2), groups ranging in size between 5 and 10 individuals are capable of pulling the *pukao* up a ramp with a length between about 23 and 32 meters.

Thus far, we have established that relatively small numbers of people can move *pukao* up ramps of reasonable dimensions by parbuckling and/or levering. Another important consideration regarding the feasibility of the Modified Ramp Hypothesis is whether or not the volumes of such ramps are reasonable. Ramps would likely be made of loosely consolidated stone and soil. I consider ramp volumes to be reasonable if they are less than the approximate volumes of corresponding *ahu*.

Physics Derivation: Ramp Volume Estimates

We wish to roughly examine the volume of material that composes a ramp with an angle of incline of θ , as depicted below in Figure 69.

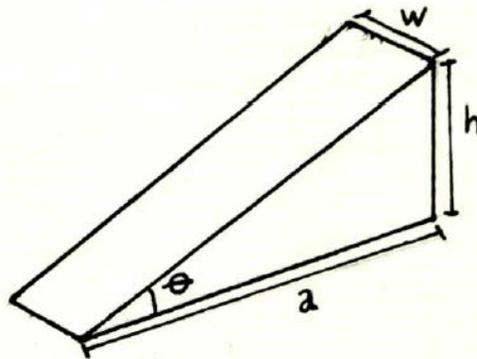


Figure 69. A ramp with an angle of incline of θ , height h , width w , and length a . In this case, h is fixed as the height of the *moai* an *ahu*, w can be approximated by the height of the *pukao* (its width when rolled on its side) plus some buffer room, and θ (with a corresponding a) can be chosen.

We know that the volume (V) of the above ramp is given by the following equation (19).

$$V = \frac{wha}{2} \quad (19)$$

We also know that the length of the ramp can be given in terms of the height and angle of incline as shown in equation (20).

$$a = \frac{h}{\tan\theta} \quad (20)$$

By substituting equation (20) into equation (19), we come to our result of equation (21).

$$V = \frac{wh^2}{2\tan\theta} \quad (21)$$

Note that we can improve on the volume estimate given in equation (21) by considering the additional volume that comes from material sloping off the sides of the ramp at a given angle of repose. In this situation, each side slope approximately forms a tetrahedral shape. The volume for a tetrahedron (V_0) is given by equation (22) below, where A_0 represents the area of its base and h represents its height. Note that h in this case is equivalent to the h in equation (21).

$$V_0 = \frac{A_0h}{3} \quad (22)$$

We wish to find A_0 in terms of the height h and a given angle of repose α . Without considering the angle of repose, we have equation (23), where x gives the width of the tetrahedron and a is the same as in Figure 69.

$$A_0 = \frac{xa}{2} \quad (23)$$

We can relate x to the known variables of α and h through the following equation (24).

$$x = \frac{h}{\tan\alpha} \quad (24)$$

Substituting equation (24) into equation (23), we come to equation (25) below.

$$A_0 = \frac{ha}{2\tan\alpha} \quad (25)$$

Note that we can find equation (26) below by substituting equation (20) into equation (25).

$$A_0 = \frac{h^2}{2\tan\theta\tan\alpha} \quad (26)$$

Substituting equation (26) into equation (22), we come to our final result in equation (27), which gives the volume of a tetrahedron in the desired terms.

$$V_0 = \frac{h^3}{6\tan\theta\tan\alpha} \quad (27)$$

Given that one such tetrahedron comes of each of the two flanks of the ramp, we combine two of the volumes given by equation (27) with the volume for the main body of the ramp given by equation (21) and come to our new result in equation (28).

$$V = \frac{wh^2}{2\tan\theta} + \frac{h^3}{3\tan\theta\tan\alpha} \quad (28)$$

Equation (28) gives a fairly accurate ramp volume estimate in which we are free to choose a reasonable ramp path width (w), ramp angle of incline θ , ramp height (h), and side ramp angle of repose (α).

Implications of Ramp Volume Estimates

The derived ramp volume equation (restated in Figure 70) can be used to plot ramp volume estimates at each of the four locations in Table 22 as a function of ramp angle of incline (Figure 71). We can compare reasonable ramp volumes in this graph to *ahu* volumes by considering the areas and approximate thicknesses of *ahu* at each location (Table 22, Figure 72). In one line of reasoning, consider the approximate volume of the *ahu* at Te Pito Kura in Table 22 (1,530 m³). If all of the volume in the *ahu* had gone into a ramp, the ramp's angle of incline would have been approximately 12 degrees (Figure 71). From Figure 67, we can conclude that that this angle of incline requires approximately 15 people to successfully parbuckle the *pukao*.

Ramp Volume

$$V = \frac{wh^2}{2\tan\theta} + \frac{h^3}{3\tan\theta\tan\alpha}$$

Figure 70. Equation for the volume of a ramp (equation 28). Here, volume is a function of the width of the ramp path (w), the combined height of the *moai* and *ahu* (h , refer back to Table 21), the angle of incline of the ramp (θ), and the angle of repose of the sloping sides of the ramp (α). I assume that w in each of the four cases in Table 21 is the height of the *pukao* plus a margin of 60 centimeters on either side. Regarding the angle of repose (considered another constant), I follow Mulloy's assumption that 60 degrees is reasonable (1970, 16).

<i>ahu</i>	Area (m ²)	Thickness (m)	Volume (m ³)
Vaihu	1,440	1.5	2,160
Ura Uranga te Mahina	900	1.5	1,350
Akahanga	1,360	1.5	2,040
Te Pito Kura	1,020	1.5	1,530

Table 22. Estimated absolute scale values for *ahu* dimensions. Dimensions from Te Pito Kura are taken from Heyerdahl and Ferdon, 1961, and the rest are taken from orthophotos developed from aerial photographs.

Ramp Volume as a Function of Angle of Incline

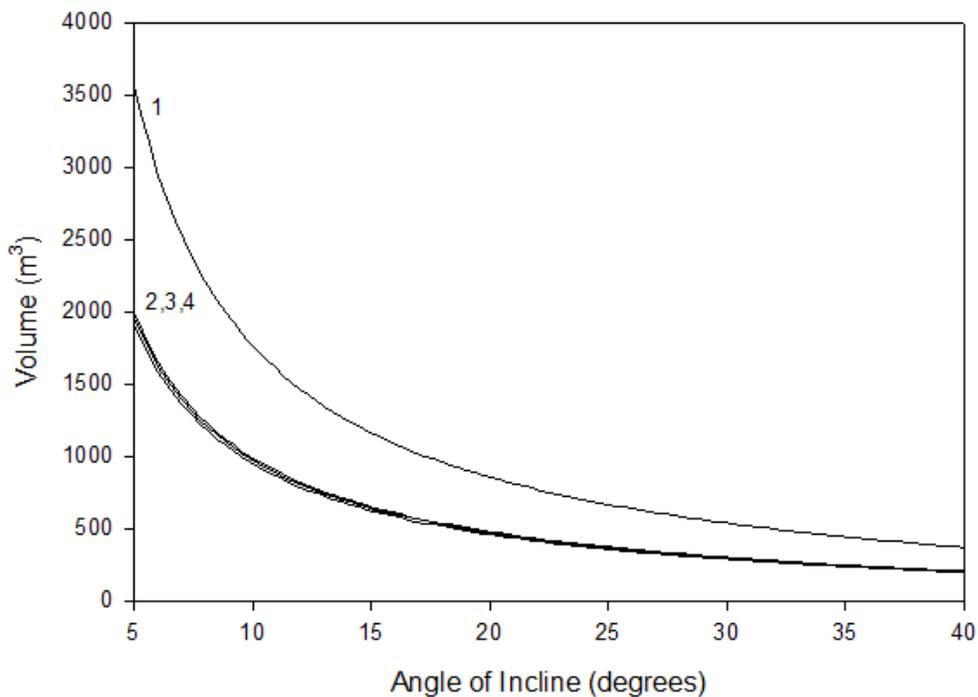


Figure 71. Ramp volume as a function of ramp angle of incline. Due to the relatively tall *moai* at Te Pito Kura, the ramp at this location (1) has the largest volume for any given angle of incline. Ramps at Vaihu, Ura Uranga te Mahina, and Akahanga (2,3,4) have similar volumes due to similar *moai* heights, with slight differences stemming only from the variable ramp path width.

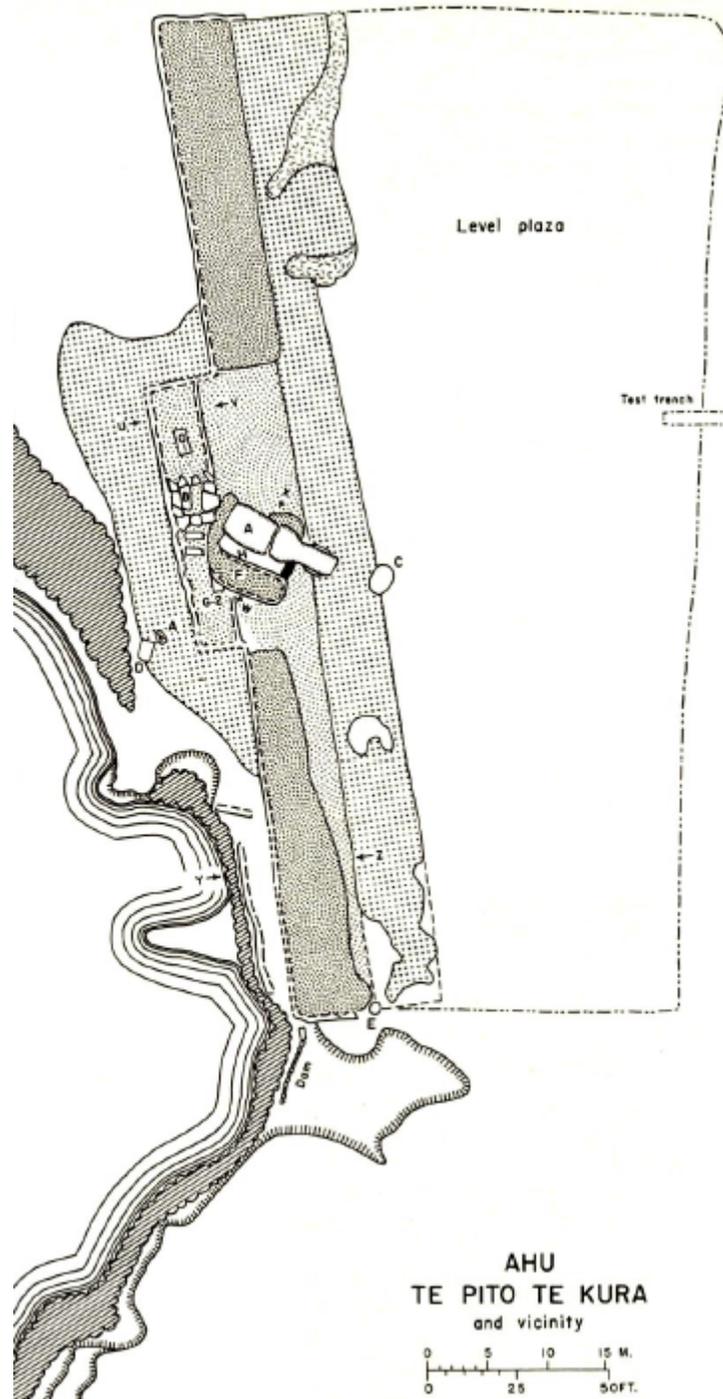


Figure 72. Scale sketch showing the extent of the *ahu* at Te Pito Kura (after Heyerdahl and Ferdon, 1961: 196). Note the fallen *moai* (a) near center and the roughly 11.5 metric ton *pukao* (c) off the front of the fallen *moai*.

Less massive *pukao* require smaller numbers of people for transport, and ramp volumes easily fit within *ahu* volume estimates in Table 22. Consider Vaihu as an example. With 10 people successfully pulling, an angle of incline of about 13 degrees or less is required (Figure 67). The volume of such a ramp would be approximately 730 m³ (Figure 71), which is well below the approximate *ahu* volume of 2,160 m³ (Table 22). Overall, the volume of the aforementioned ramp would spread across the area of the *ahu* at Vaihu with a thickness of about half of a meter. For analogy, this corresponds to the volume of material spread with a thickness of about 14 centimeters across an American football field (area of about 5,351 m²). Overall, ramp volume estimates support Thomson's (1891, 449) idea regarding *pukao* ramps that "the stones which formed the foundation of the roadway were disposed of in building the wing-extensions of the platform."

A final line of reasoning possible with the graphs produced in this section considers the remains of a possible ramp feature observed in the field at Ura Uranga te Mahina (Figure 73). Specifically, we can verify that a ramp with the observed length would be feasible for *pukao* transport. A length of about 13 meters and a *moai/ahu* height of about 8 meters dictates a ramp angle of incline of about 32 degrees. A ramp with these dimensions would have had a reasonable volume (less than 500 m³, Figure 71), and about 8,000 N of force would have been required to roll a *pukao* up the ramp through parbuckling. This roughly corresponds to the pulling force of about a dozen individuals, so we find that it is physically feasible for the stone body in Figure 73 to represent the remnants of ramp with roughly original orientation and extent.



Figure 73. Spread of stones at the *ahu* at Ura Uranga te Mahina measuring about 13 meters in length (photo by Carl Lipo, 2014). Note that *pukao* 29 (on the lower end of the possible ramp remains) has an almost perfectly circular cross section, with a min/max diameter of about 0.99.

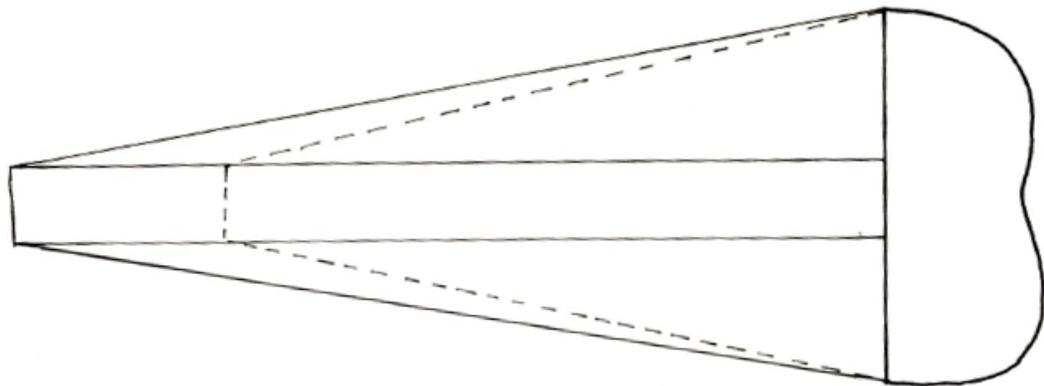
Modifications to Ramp Hypothesis

Physically rolling a *pukao* up a ramp holds two advantages over sliding. First, a mechanical advantage associated with parbuckling halves the force required to move a *pukao* up an incline. Given the added force of friction associated with sliding, parbuckling more than halves the force required to move a *pukao* up an incline. Second, rolling takes advantage of the force of friction between the *pukao* and ground instead of fighting this force.

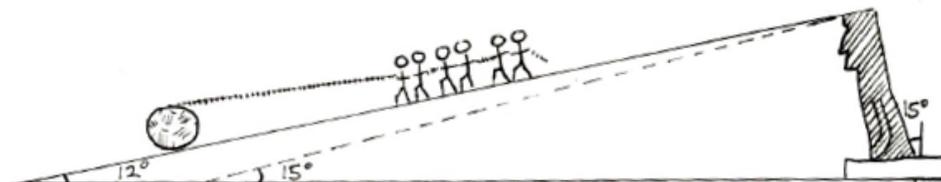
When a ramp is built in front of a *moai*, the *moai* may be oriented in a couple of different ways: as it was when it walked (leaning forward) or as it is in its final state (erect). We know that the Rapanui modified the bases of *moai* at some point after they reached the *ahu* in order for the *moai* to stand erect (Figure 74). The forward-leaning orientation (Figure 75) best explains the evidence for three reasons. First, the forward lean serves to slightly reduce the required height and length of the ramp. Second, it serves to prevent the *moai* from toppling backwards due to the weight of the ramp. Finally, it aids the placement of the *pukao* on top of the *moai* once the former reaches the top of the ramp.



Figure 74. Image illustrating the convergence of two flat surfaces (marked with black lines) on a fallen *moai* base just east of Tongariki (photo by author, 2014). In this case, the *moai* faces upwards. The upper flat base surface in the photo may represent the surface when the *moai* leaned forward, while the lower flat base surface in the photo may represent the surface when the *moai* was in the process of final erection. Note the backward/forward lean angle of approximately 23 degrees.



TOP



SIDE

0 2 4 6 8 10 meters

Figure 75. Scale sketch showing an approximation of a reasonable ramp coming off of the front of a forward-leaning *moai* at the Vaihu *ahu*. About 10 people would be required to pull the *pukao* preform up the 15 degree incline. The top view shows the spread of the ramp when we consider an angle of repose about 30 degrees.

The third point mentioned above is significant and ultimately links back to the presence of base indentations on *pukao*. Mulloy (1970, 16) notes “the delicate problem of tipping the topknot” once it reaches the top of the *moai*. However, the forward lean of the *moai* reduces the angle of passage for tipping. The presence of a top cylinder may aid the tipping of *pukao* when one considers the possibility of wrapping rope around the top cylinder and pulling from behind the *moai*. Recall that only *pukao* 65 does not possess a top cylinder, but also recall that this *pukao* is quite conical in form.

The conical form of this *pukao* would serve a similar function as the presence of a top cylinder when tipping the *pukao*. Also note that tipping over the front of the *moai* would be more stable than tipping over the side given that the former situation involves tipping over the short axis of the *pukao* oblong cross section.

When the *pukao* rests on the top of the *moai* following tipping, we come to recognize a likely functional aspect of the base indentation not considered in other hypotheses. Specifically, based on the forward lean of the *moai*, the vertical projection of the center of mass of the *pukao* moves toward the front of the *pukao* base indentation (Figure 76). If the projection of the center of mass extends beyond the front of the *pukao*, then the *pukao* requires additional support to maintain its position atop the *moai*. Generally, road *moai* that the Rapanui walked include forward lean angles of more than 15 degrees (Lipo et al. 2013, e.g. Figure 74). These forward lean angles put the projection of the *pukao* center of mass close to the front edge of the base indentation (Figure 76 and Table 23). In this precarious situation, one may expect external support to be required, as envisioned in Mulloy's hypothesis (Figure 12). However, the base indentation, and specifically its pronounced back edge (Figure 77), serve to prevent the *pukao* from toppling forward when the ramp is removed and the *moai* is brought to an erect position. Thus, the base indentation has a function only during the final stage of erection. Even though González believes that the base indentation served a function in balancing the *pukao* once it rests on top of the erect *moai* (Ruiz-Tagle 2005, 58), we know from measurements in Table 6 that this is not the case. Overall, the presence and orientation of the *pukao* base indentations singularly support the Modified Ramp Hypothesis.



Figure 76. Sketch of side view of *moai* and *pukao* showing the vertical projection of the *pukao* center of mass (CM) when given a forward *moai* lean angle of ϕ . Here, ϕ is defined as the angle that places the projection of the CM directly above the front edge of the base indentation. In cases where the forward *moai* lean angle approaches ϕ , the back edge of the base indentation comes to serve a function as a “lip” that prevents the *pukao* from toppling forward.

Location	<i>Pukao</i> Number	d (m)	h (m)	Φ
Hekii	57	0.177434	0.570346	17.28
Hekii	60	0.275483	0.807894	18.83
Anakena	65	0.239446	0.460120	27.49
Anakena	68	0.212213	0.514347	22.42

Table 23. Uncalibrated measurements between *pukao* features and centers of mass. Distance d gives the horizontal distance between the center of mass and the forward edge of the base indentation, and distance h gives the vertical distances between the base of the *pukao* and the center of mass (refer back to Figure 35 for clarification). Angle ϕ corresponds to that in Figure 76 and is given by the inverse tangent of d/h. Unfortunately, the measurements in this table can only be observed in the four *pukao* above due to the poor condition, partial burial, and/or resting faces of other *pukao*.



Figure 77. Textured model of *pukao* 57 from Hekii showing the pronounced back edge of its base indentation (about 4 centimeters deep) in the upper right and the relatively indistinct front edge of its base indentation near the center. As seen in Table 23, *pukao* 57 has a relatively low value for phi, which may explain why the back edge of its base indentation is relatively pronounced.

The evidence indicates that the hypothesis for *pukao* transport by rolling up a ramp most parsimoniously explains the archaeological record. It is also physically feasible. Building a ramp would 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).

Future Research

Future research should look more closely at spatial variability in the physical form of *pukao*. In this study, I used sector divisions in order to make spatial comparisons, but any imposed divisions such as mine lead to the modifiable aerial unit problem. Attempts at spatial interpolation for visualizing dimensions of *pukao* variability across space met with limited success, but ordination procedures may shed

additional light on the spatial distribution of *pukao* variability. Unfortunately, the limited sample size of *pukao* in many cases may limit the detection of significant spatial trends in *pukao* variability.

Additionally, 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. However, the tensile strength of rope made of *Triumfetta semitriloba* is poorly documented, and we lack a clear understanding of the amount of plant material required to make a given length of rope. 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.

Closer study of *ahu* may further test the previous conclusions regarding *pukao* transport that are based primarily in the study of *pukao* variability. Examining the distribution of soil and stone cobbles in and around *ahu* may or may not reveal evidence of past ramp features. A large complication in such a study is that stones from many *ahu* have been incorporated into walls and other features associated with past sheep ranching.

Finally, work with cosmogenic dating may give us some sense of the timing of *pukao* production. One option is the application of optically stimulated luminescence (OSL) dating to sediments beneath *pukao* and other scoria bodies. OSL dating is based on the fact that ionizing radiation from isotopes of uranium, thorium, rubidium, and potassium is absorbed and stored in the crystal lattice of buried sediments. When the crystal lattice is exposed to solar radiation, it expels its stored radiation. The rate of buildup of ionizing radiation is known in certain minerals, and the buildup in a given

sample can be measured by release in controlled laboratory settings. This enables the successful dating of the last time that a sample experienced sunlight. By measuring OSL of sediments found beneath blocks of scoria inland of *ahu* and in Puna Pau, we can learn when these objects came to rest in their present position – the event at which grains on the surface became buried. We can also use this technique to date the time when fallen *pukao* came to rest. The former application is more likely to provide estimates on when the Rapanui were producing *pukao*. OSL dating works well with quartz and feldspars. Given the mafic nature of the Rapanui substrate, OSL dating must in this case rely on feldspars (primarily plagioclase) present in buried sediments.

Another form of cosmogenic dating that can be applied to *pukao* movement is cosmic ray exposure (CRE) dating. This technique takes advantage of the known rates of decay for certain cosmogenic radionuclides such as beryllium-10 and helium-3. An examination of helium-3 may be the most fruitful on Rapa Nui given that this isotope is frequently reported in olivine and pyroxene (both mafic minerals, Gosse and Phillips 2001, 1516). Unfortunately, most successful applications of helium-3 CRE dating have been on the scale of thousands of years (Figure 78, Gosse and Phillips 2001, 1517).

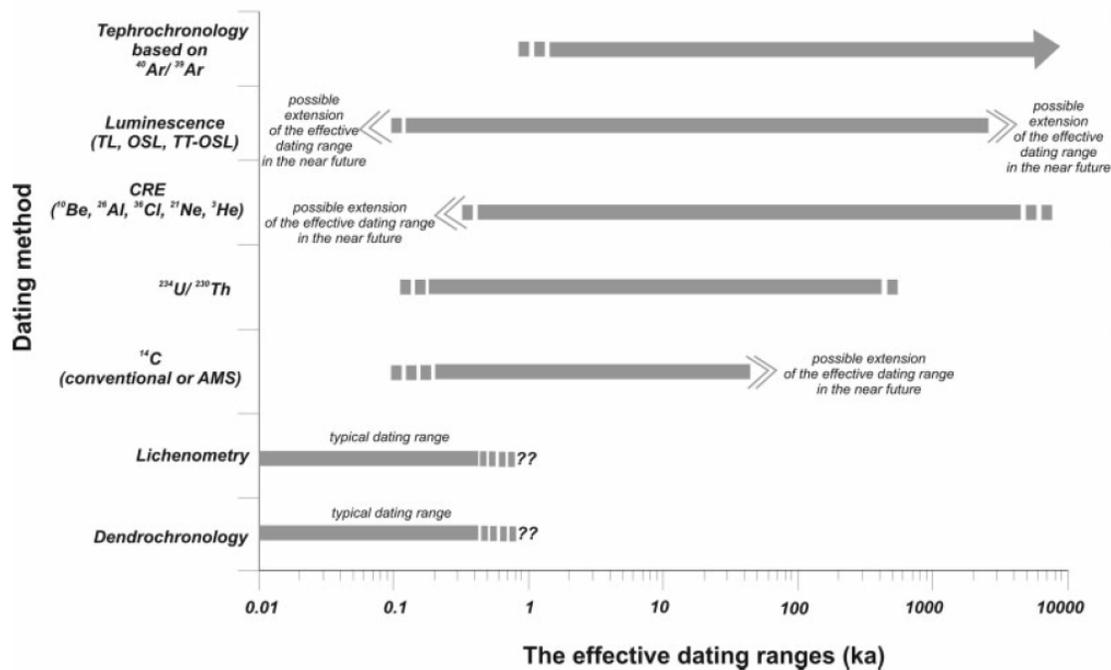


Figure 78. Various dating methods and their effective ranges (after Pánek, 2015: 170). Dating methods with clear ties to *pukao* production and effective ranges between 0.1 to 1 ka are most likely to expand our understanding of a chronology for *pukao* production. Lichenometry has a relatively recent effective range when compared to the OSL and CRE dating methods.

A final possible method for dating *pukao* production and transport involves lichenometry. Lichenometry takes various approaches, but it generally dates the exposure of a rock surface by considering the nature and extent of lichen growth and estimating past lichen growth rates based on present growth rates. One limitation in applying lichenometry to rock surfaces on Rapa Nui is that very few dated reference lichen substrates exist. However, Gerhard Follman (1961) successfully used lichenometry in order to date *moai* and *ahu* surfaces, and Rutherford et al. (2008) have since provided some documentation of lichen growth at Ahu Tahira. Lichenometry has

been used to date the initial creation of *ahu* surfaces with ages greater than 400 years and errors less than 10 percent (Rutherford et al. 2008, 43). No study has yet examined lichens on *pukao*, but Figures 25 and 27 establish that lichen has colonized *pukao* surfaces for at least one hundred years.

Summary

The Modified Ramp Hypothesis for *pukao* transport best explains the archaeological record and is physically feasible. This form of transport has never before been proposed, but it includes elements of the traditional Ramp Hypothesis and Mulloy's Simultaneous Set Up Hypothesis. The Modified Ramp Hypothesis first involves the construction of a ramp (ranging in angle of incline between 10 and 35 degrees) off the front of a forward-leaning *moai* after the *moai* is brought to stand on an *ahu*. Ramp material, which can be used to help walk the *moai* up a small height to the top of the *ahu*, can include stone, coral fragments, and soil. The *pukao* preform is rolled up the ramp primarily by a group of up to 15 individuals parbuckling from above with possible levering aid by up to three people from below. Breaks or steps in the ramp may ease this stage of transport. Upon reaching the top of the ramp, the preform is pivoted in place by excavating the ramp material beneath the preform, manipulating the preform through levering, and/or manipulated the preform by using rope. The forward lean of the *moai* eases the tipping of the preform so that the base indentation fits on the *moai*'s top. Any refinishing of the *pukao* occurs at this point. Material is then carved from the rear of the *moai*'s base so that the *moai* tilts backward and is brought to its final erect position. Ropes may stabilize the *moai* during this transit, and the *pukao* base indentation prevents the *pukao* from toppling forward. The final step is the

removal of the ramp: Stones can be incorporated into the wings of the *ahu*, and soil can be used in nearby garden plots.

Future research may refine aspects of the above reconstruction for *pukao* transport. However, it is significant that the archaeological evidence for *pukao* transport, just like that for *moai* transport (Hunt and Lipo 2011), supports a method involving relatively few people. Contrary to popular ideas that connect monumentality with larger groups of laborers working under a centralized authority, neither *moai* nor *pukao* transport required the coordination of large groups of people.

Appendix

Year	Name(s)	Purpose of Visit
1722	Jacob Roggeveen Cornelis Bouman	Dutch expedition in search of <i>Terra Australis</i>
1770	F.A. de Agüera y Infanzon Felipe González de Haedo	Spanish territorial mission
1774	James Cook Johann and Georg Forster	British exploratory mission
1786	Jean François Galaup de la Pérouse	French exploratory mission
1866	Hippolyte Roussel	French missionary
1868	Linton Palmer	British survey expedition
1877	Alphonse Pinart	French exploratory expedition
1882	Wilhelm Geiseler	German anthropological expedition
1886	William Thomson	Smithsonian expedition
1914	Katherine and Scoresby Routledge	British private / museum-based expedition
1940	Alfred Métraux	French ethnographic expedition
1955	Thor Heyerdahl	Norwegian archaeological expedition

Appendix Table 1. List of past visiting groups with references to *pukao*. Jacob Roggeveen is credited with the European discovery of Rapa Nui.

Model Generation, Filing, and Observation Strategies

Refined workflow for *pukao* textured model generation:

- Align photos with high accuracy and disabled preselection (typically takes between 3 and 13 hours)
- Optimize alignment (typically takes 5 minutes)
- Compute alignment quality for individual photos
- Disable cameras that have quality values lower than 0.5
- In situations with a multitude of photos, disable duplicate cameras and thin those with quality values lower than 0.7
- Save sparse point cloud
- Generate dense point cloud with high quality and aggressive filtering (Note that aggressive filtering eliminates some detail by filtering outliers, but with the scale of the imagery in use, aggressive is okay - typically takes between 3 and 7 hours.)
- Save dense point cloud
- Generate mesh based off of arbitrary surface type and dense point cloud (typically takes around 1 hour)
- Build model texture using generic approach (typically takes less than an hour)

- Save entire project
- Generate and save accuracy report
- Backup all files on computer and external hard drive

Model file management scheme:

“Pukao 2014 Project”

>Place Name (e.g. “Vinapu”)

>“Photos”

>Pnumber (e.g. “P2,” all photos of individual numbered *pukao* used in model)...

>“Generic” (overview photos of site)

>Pnumber (e.g. “P2,” file including all model files of an individual *pukao*)

>“Unclipped”

>Photoscan project file (e.g. “Pukao2.psz”)

>Project report (e.g. “Pukao2.pdf”)

>Exported point file (e.g. “Pukao2” .obj file)

>Exported model file (e.g. “Pukao2mod” .obj and .mtl files)

>“Clipped”

>Photoscan project file (e.g. “Pukao2clip.psz”)

>Project report (e.g. “Pukao2clip.pdf”)

>Exported point file (e.g. “Pukao2clip” .obj file)

>Exported model file (e.g. “Pukao2modclip” .obj and .mtl files)

Preliminary Analysis of Textured Models:

In Photoscan:

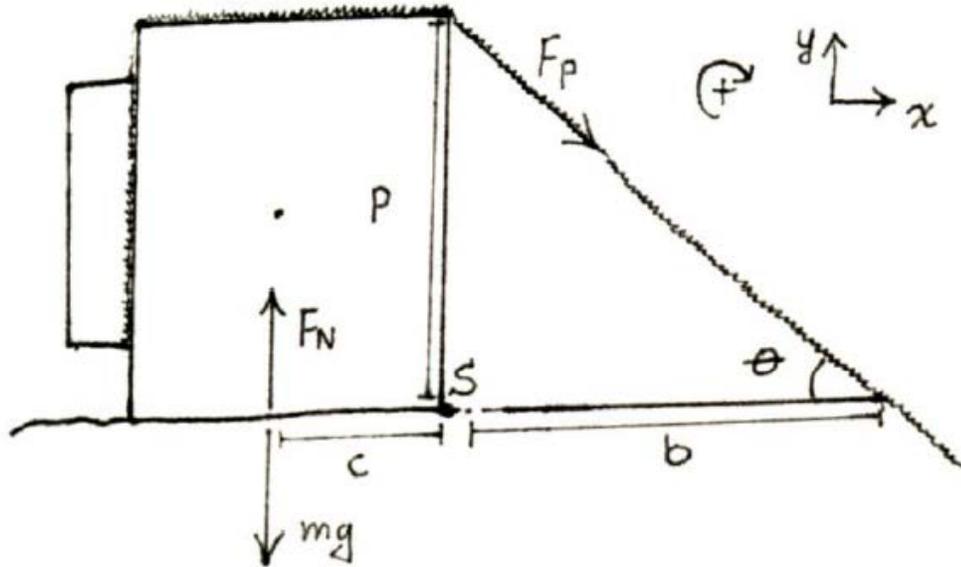
- Record the resting position of the *pukao*.
- Record whether or not the full *pukao* is exposed.
- Record the state of the *pukao*.
- Clip model so that it includes only points associated with the *pukao*.
- Fill 100% of the holes in the *pukao* model.
- Record the volume of the *pukao* and associated error

In Meshlab:

- Apply the APSS colorize curvature filter to the mesh using the default settings – This colorizes the vertices of the mesh using the curvature of the underlying surface and enhances subtle and narrow etchings in the *pukao* surface.
- Use the z-painting tool in order to mark etchings and indentations in the *pukao* surface in red. Only markings that appear to have been created outside of weathering should be marked. Export the marked mesh as a .obj file. (In the filing scheme previously given, the marked .obj files go into the “clipped” file associated with the given *pukao*.)
- Using the PickPoints tool, select each marking and assign it a unique number going upward from 1 on each *pukao*. Save this information as a .pp file with the aforementioned .obj file.
- After marking and labeling all features, record the presence and absence features and take measurements of key dimensions.

Additional Physics Derivation: Final Flipping of *Pukao*

We wish to examine the force required to flip the *pukao* over once it reaches the top of the ramp and is aside the top of the *moai* as shown below in Appendix Figure 1.



Appendix Figure 1. A possible means of flipping a *pukao* from its side onto its base using a rope tied around the top cylinder and trailing off the side of the *moai*. The force on the *pukao* due to gravity acts downward at the center of mass of the *pukao* and is given by mg , where m is the mass of the *pukao* and g is the acceleration due to gravity. The normal force due to the ramp acts perpendicular to the ramp and is designated by F_N . A person exerts a force F_P that acts at an angle θ above the top surface of the *moai* (of length b). In this case, F_P pivots the *pukao* around the pivot point S . The lever arm of F_P is p , and the lever arm of mg is c , as seen above. Note that the *pukao* may be flipped over the front or the side of the *moai* depending on where the ramp is located.

We wish to find an expression that gives the force F_P required for pivoting the *pukao* round the point S . We begin by considering the situation in which the *pukao* is in a state of static equilibrium and the sum of torques is zero. We thus have equation (29), in which F_{Px} is the component of F_P acting along the x -direction and perpendicular to the lever arm of length p .

$$\Sigma\tau = 0 = F_{Px}p - mgc \quad (29)$$

We know that F_{px} is related to F_p through equation (30).

$$F_{px} = F_p \cos\theta \quad (30)$$

Thus, we can substitute equation (30) into equation (29), solve for F_p , and come to equation (31).

$$F_p = \frac{mgc}{p \cos\theta} \quad (31)$$

Note that we can find equation (32), which relates known lengths to θ .

$$\cos\theta = \frac{b}{\sqrt{b^2 + p^2}} \quad (32)$$

By substituting equation (32) into equation (31), we come to our final result given by equation (33).

$$F_p = \frac{mgc\sqrt{b^2 + p^2}}{pb} \quad (33)$$

Using equation (33) and applying a given *pukao* mass (m), distance to *pukao* center of mass (c), width of *pukao* being flipped (p), and base of *moai* top (b), we can now find the force F_p required to flip the *pukao*.

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