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Article *in* Journal of Archaeological Science · November 2019

DOI: 10.1016/j.jas.2019.104994

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Journal of Archaeological Science 111 (2019) 104994

Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: www.elsevier.com/locate/jas

New excavations in Easter Island's statue quarry: Soil fertility, site formation and chronology

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ARTICLE INFO

Keywords:
Easter island (Rapa Nui)
Moai
Soil fertility
Bayesian model
Dryland agriculture

ABSTRACT

This study centers on excavations in the inner region of Rano Raraku, the megalithic statue (*moai*) quarry of Rapa Nui (Easter Island). In Rano Raraku a transformed landscape is reconstructed based upon soil chemistry, micromorphology, and macro and micro-botanical data framed within a stratigraphic and radiocarbon informed Bayesian model that is the first for Rapa Nui. We focus on *moai* RR-0001-156, one of only three *moai* in the island-wide corpus known to be embellished with a dense suite of cohesive petroglyph motifs. Our results confirm a cultivated landscape present on the inner south and east slopes of Rano Raraku that included sweet potato and probably bottle gourd along with Polynesian transfers banana, taro, and paper mulberry from the 14th century AD continuing into the early 19th century AD. During this time of sociopolitical transformation and land use change across the island labor-intensive rock gardens were developed to increase productivity as soil fertility declined in the context of deforestation and perhaps drought while the pan-island center of ‘Oroŋo (Orongo) emerged at Rano Kau with an intensive ritual focus on fertility. Rano Raraku in sharp contrast had (and still has) extremely fertile soils that are the weathering byproduct of lapilli tuff sediments generated from the quarrying process and localized human activity. This study validates Rano Raraku as the major *moai* production center, establishes chronological parameters for the unique embellished statue and describes agricultural fertility to hypothesize a rich, multi-use landscape for Rano Raraku inner region that is unparalleled elsewhere on Rapa Nui.

1. Introduction

The remote Polynesian Island of Rapa Nui (Easter Island) lies in the eastern Pacific Ocean and the Southern Hemisphere at 27° 9′S latitude and 109° 26′W longitude. Debate on social transformation is linked to variant interpretations of the timing, causation and effects of deforestation and environmental degradation (Kirch, 1984; Flenley et al., 1991; Lipo and Hunt, 2016; Horrocks et al., 2012b; Cañellas-Boltà et al., 2013; Mulrooney, 2013), demographic change (Anderson, 2002; Puleston et al., 2017) and *moai* production (Cristino and Vargas, 1980; Van Tilburg, 1987, Van Tilburg, 1988; 1994; Van Tilburg and Lee, 1987; Gonzalez et al., 1988; Vargas, 1988; Vargas et al., 2006; Van Tilburg et al., 2008). In this paper we bring together multiple data sources to reconstruct a dynamic landscape in Rano Raraku (Rano a Raraku; hereafter, Rano Raraku) where precisely 91.34% of known megalithic *moai* were produced. We describe recent excavation results from Quarry 2 in the Rano Raraku inner region and emphasize new geoarchaeology, radiocarbon determinations and botanical data. This study reveals the central role of *moai* quarrying in creating the inner region's uniquely fertile soils capable of producing high yields when available data otherwise indicate inadequate food production and substantial social challenges.

Polynesian discovery of Rapa Nui took place as early as AD 900 and probably not later than AD 1000–1100 (Green, 1966, 1998; Van Tilburg, 1994; Stevenson and Haoa Cardinali, 1998; Mulrooney et al., 2011; Mulrooney, 2013; Montenegro et al., 2016; Kirch, 2017a, 2017b).

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https://doi.org/10.1016/j.jas.2019.104994
Received 21 December 2018; Received in revised form 13 July 2019; Accepted 5 August 2019
Available online 30 September 2019

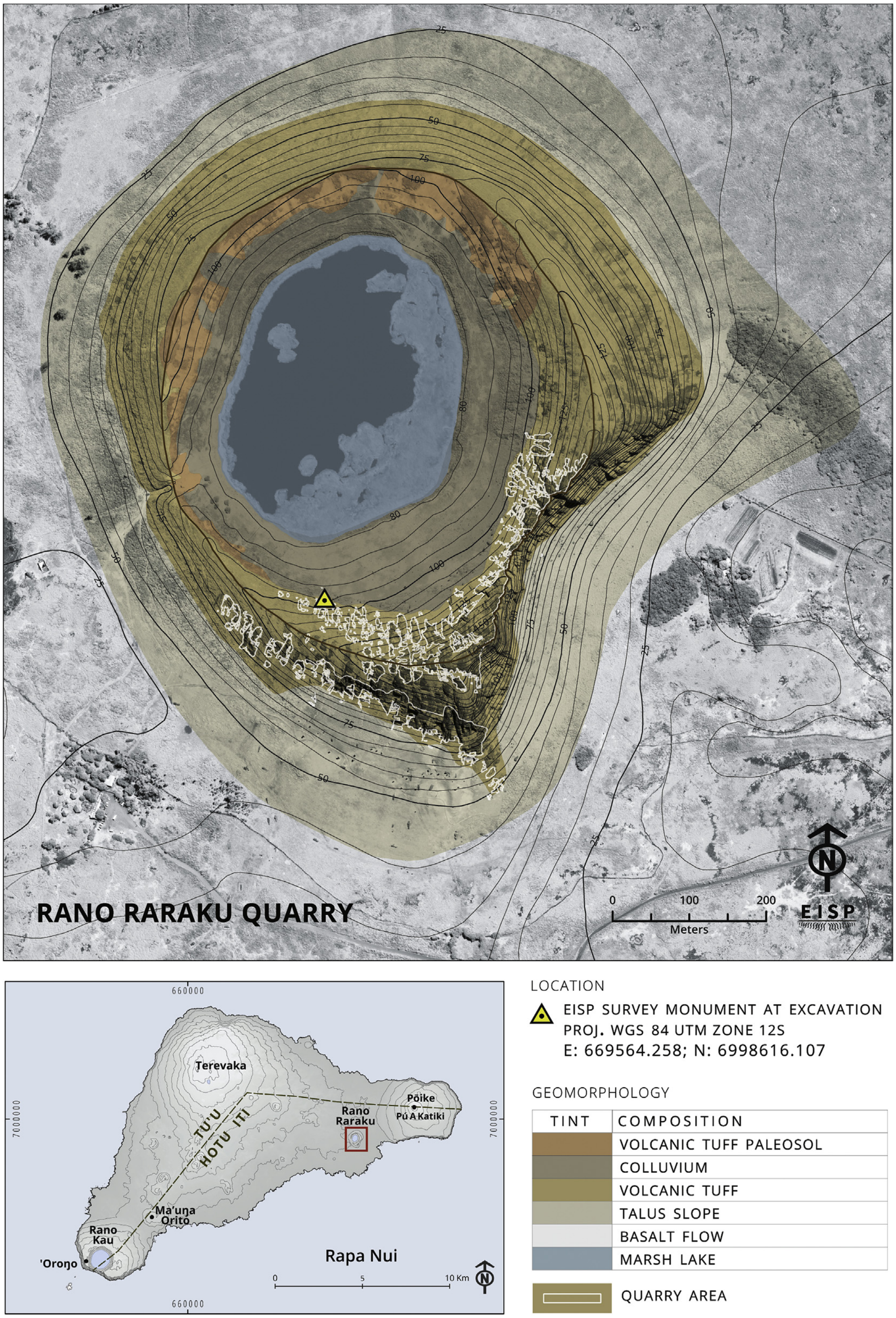


Fig. 1. Detailed topographic and archaeological survey map of Rano Raraku, Easter Island's statue quarry, with quarried objects outlined. Contour interval = 5 m ©EISP Archives and Database. Base map Instituto Geográfico Militar de Chile, 2004. Satellite image ©Digital Globe, Inc. Geomorphic overlays R.K. Dunn et al. (2013); Supplemental data: Routledge (1919); Cristino et al. (1981); Map of Rapa Nui (Easter Island): sociopolitical divisions drawn, place names in text. Cartographic illustrations by Alice Hom.

Rano Raraku is a prominent geological feature on the 163.6 km^2 island and included within Hotu Iti, the lower-ranked of two unified sociopolitical regions (Fig. 1). Rano Raraku would have attracted early attention due to its rainwater fed lake (*rano*), one of the island's major concentrations of fresh water (Routledge, 1919; Skjølsvold, 1961; Herrera and Custodio, 2008; DiNapoli et al., 2019). Rano Raraku is made up of lapilli tuff, which is ideal for carving (Pauly et al., 1994; Rauch and Weber, 1994; Wendler et al., 1996; Charola, 1997).

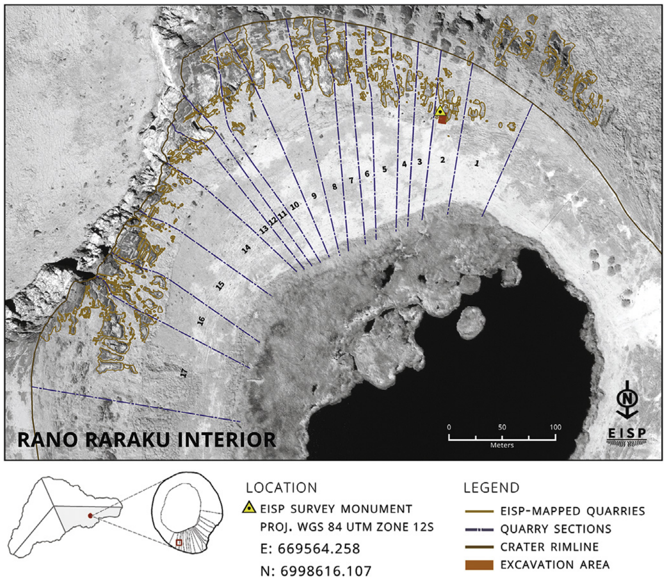


Fig. 2. Map of Rano Raraku Quarry Inner Region: 17 quarried sections drawn, Quarry 2 excavation site indicated; Cartographic illustrations by Alice Hom; ©EISP Archives and Database.

Polynesians have a long cultural tradition of land clearance and landscape transformation to establish agriculture (Kirch, 2006, 2017a; Kirch et al., 2011; Kirch et al., 2012, 2017b). Stone and wood carving industries are well-developed in Eastern Polynesia and quarrying of stone resources probably commenced at Rapa Nui settlement (Skjølsvold, 1961; McCoy, 1976, 2014; Ayres et al., 1998). The Easter Island Statue Project (EISP) directed by Jo Anne Van Tilburg with Cristián Arévalo Pakarati conducted an island-wide inventory accounting to date for 1693 stone sculptural objects (monolithic, portable, and fragments) in the context of over 27,000 georeferenced sites, features, or objects recorded by multiple survey teams (McCoy, 1976; Cristino et al., 1981; Gonzalez et al., 1988; Van Tilburg, 1990; Bahamondez, 1994; Stevenson and Haoa Cardinali, 1998, Stevenson and Haoa Cardinali, 2008; Wozniak, 1998; Stevenson et al., 1999, 2018; Vargas et al., 2006; Van Tilburg et al., 2016).

Recent excavations reported here focus on two of 21 upright, partially buried statues on the Rano Raraku inner region slope (Figs. 2 and 3a; RR-0001-156 and RR-0001-157 (hereafter 156 and 157)). *Moai* 156 and 157 are in Quarry 2, one of 17 identified and mapped inner region quarries (Van Tilburg et al., 2005,2008; Van Tilburg and Arévalo Pakarati, 2009, 2014) (Fig. 2). These *moai* were selected due to their slope location and ethnographic and ethnohistorical records but also to update previously inadequate reporting and clarify the chronological trajectory of the *moai* corpus. Petroglyphs superimposed on the dorsal sides of both statues create tableaus that are relatively unique (Fig. 3b); only one other *moai* is similarly embellished. This second embellished moai is known as Hoa Hakananai'a, collected in 1868 from building EISP-13 at the ceremonial site of ‘Oroŋo, Rano Kau in Tu'u, the higher-ranked of two sociopolitical regions (Routledge, 1919; Métraux, 1940; Van Tilburg, 2006). The low relief petroglyphs on the dorsal side of the ‘Oroŋo *moai* are icons emblematic of *taŋata manu* (“birdman”) fertility rituals (Routledge, 1919; Métraux, 1940; Englert, 1978). The archaeological research impetus for the Rano Raraku excavations was to examine the structural and environmental interaction of ideology with material culture production in one area of the island. Specific goals included clarification of *moai* characteristics and production methods, documentation of the ambient environmental characteristics of Rano Raraku inner region, clarification of human use of the area, and comparative iconography of the petroglyphs. The established view (Skjølsvold, 1961; Mulloy, 1970) was that *moai* 156, 157 and the other complete *moai* partially buried upright on the slope were set temporarily in constructed earthen mounds prior to removal or abandoned. However, our excavations refute this view and reveal base structural features including carved bedrock pits intended to hold the statues upright with gravel and boulder packing. Our study confirms that the accumulated sediments above these are secondary deposits. The *moai* 156 excavation results are reported here; however, the details of the inner slope bedrock geology, macroartifact analyses, and new comparative interpretations of the petroglyphs are beyond the scope of this paper and will be published separately.

A major outcome of this research is new insight into the multi-use of Rano Raraku inner region as established by the detailed study of sediment composition and contents describing agricultural land use history. Erosion and deposition are recognized as significant processes (Mieth et al., 2002; Mieth and Bork, 2005, 2018; Sáez et al., 2009; Horrocks et al., 2012a; Cañellas-Boltà et al., 2013) for Rapa Nui, including in major water courses (Vogt and Kühlem, 2017), but when these processes occurred in Rano Raraku and how they are tied to land use were unknown prior to this study. While late Holocene inner region land clearance is established by paleoecology (e.g., Flenley et al., 1991; Mann et al., 2008; Sáez et al., 2009; Rull et al., 2010; Horrocks et al., 2012a), it was assumed that associated human activity was exclusively industrial until initial indications of agriculture in the inner region were derived from a lake core and a dryland soil profile on the north side of the quarry with microbotanical evidence for *Colocasia esculenta* (taro), *Ipomoea batatas* (sweet potato), *Musa* (banana sp.) and possibly *Lagenaria siceraria* (bottle gourd) (Horrocks et al., 2012a: 779). This microfossil evidence occurs at approximately cal AD1320–1440 (95% probability) (Horrocks et al., 2012a: 773, recalibrated from the original published date) and suggests the co-existence of quarrying and gardening at that time. Inversion issues with dates derived from lake coring limit our ability to address duration but the dating of cultivars confirms their presence and timing in Rano Raraku inner region.

The circumstances and potential productivity of Rapa Nui farming are key to understanding island-wide demographics and social change in the apparent face of environmental degradation. However, it is important to note that there are significant gaps in the knowledge of variable soil fertility across the island. This study emphasizes the physical and chemical stratigraphy revealed in the excavation and the botanical remains within these layers and presents a Bayesian model developed from radiocarbon determinations. This allows us to refine the chronology of Rano Raraku inner region landscape transformation during a slow-down of previously intensive quarrying activities and an associated agricultural expansion.

2. Rano Raraku background

2.1. Rano Raraku environment and geology

Rano Raraku (E: 669564.258; N: 6,998,616.107) is within the Hotu Iti socio-political region (Fig. 1). The island resulted from the coalescence of three inactive volcanoes dating to less than 1 mya and creating a substrate of mixed weathered basaltic flows (Chubb, 1933; Louwagie et al., 2006). The maximum elevation above sea level (ASL) varies in the literature but is associated with Ma'uŋa Aroi (hereafter, Terevaka) at 525 m ASL. The island's climate is subtropical with average temperatures of 21 °C. A major limiting factor for farming is variable rainfall ranging from 2100 mm/y in the upper elevations to as low as 630 mm/y within the rain shadow on the northwest coast (Stevenson et al., 2015). Rainfall in Rano Raraku inner region was measured throughout the excavations reported here and in 2011–12 registered 875 mm/yr with the highest rainfall at 270 mm for the month of January (Van Tilburg and Arévalo Pakarati, 2014).

Geological mapping confirms that Rano Raraku is a semi-circular erosional geomorphic feature with an elevated rim measuring ca. 800–1000 m across, ca.100 m ASL in the west and north, and ca.160 m

Fig. 3. a) Pre-excavation view of standing *moai* 156 (right, foreground) and 157 (left, background), 2009; view to the south. Photo ©EISP Archives and Database. b) Excavation of south side of 156: dorsal view inscribed surface. Note the north excavation is described in this paper. Photo ©EISP Archives and Database. c) Carved bedrock features associated with *moai* 157 (background, left) and 156 in foreground out of the photo: pit (*pú*) 55 cm deep, 260 cm circumference (rim) and 185 cm (bottom); selected rock packing and pedestal under *moai* 157 (background, left); Photo ©EISP Archives and Database. d) View of head/face 230 propped against the right side of *moai* 156. Note other gravel packed along the base, 2014; Photo ©EISP Archives and Database.

ASL in the south and east (Dunn et al., 2013). Rano Raraku is situated at about 50 m ASL on low-relief plains of basaltic flows which emanate from Terevaka (Vezzoli and Acocella, 2009). Previous geological studies (e.g., Baker, 1973; Van Tilburg, 1988aVan Tilburg, 1988b; Overland and Hjelle 2009) have suggested, presumably based on proximity, that Rano Raraku is an isolated tuff feature associated with Pú A Katiki (Pōike; 352 m ASL). The hyalotuff forming Rano Raraku bedrock is of phreatomagmatic origin (Baker et al., 1974; González-Ferran and Baker, 1974; Baker, 1993; Moreno, 1994; Gioncada et al., 2010) and therefore difficult to date. The tuff is especially suitable for carving but not for preservation due to its relatively high porosity, low bulk density and homogeneity across the area (Chubb, 1933; Baker, 1993; Van Tilburg et al., 2008; Gioncada et al., 2010).

Denuded tuff is exposed along the inner and outer south and east slopes of Rano Raraku, while north and west inner slopes are dominated by unconsolidated, deeply weathered tuff outcrops covered by non-native grasses and shrubs. The 17 inner region quarries are marked by standing *moai* and quarried surfaces reach to the rim while lower slopes are buried in colluvium (Fig. 2). Extension of quarrying below the standing *moai* in Quarry 2 is suggested by early observation (Skjølsvold, 1961) and surmised by current studies preceding further investigation (Van Tilburg and Arévalo Pakarati, 2014).

Vegetation at Western contact (AD 1722) was largely grass and scrub with paleoenvironmental data indicating that a type of native palm and other trees covered most of the island prior to human colonization (Flenley, 1979, 1998; Flenley and King, 1984; Flenley et al., 1991; Orliac, 1998, 2000; Butler and Flenley, 2010). Palm provided a minor food source but was useful for house construction, *moai* production, shade gardening, and soil stabilization. The palm was overharvested in nearly all parts of the island from AD 1250 (Stevenson et al., 2006; Mieth and Bork, 2010, 2018; Ingersoll and Ingersoll, 2018), although preliminary reports suggest at least one protected grove remained longer in the island's highland interior (Vogt and Moser, 2010; Vogt and Kühlem, 2017). While parts of the island's soil record beyond Rano Raraku is lost to erosion, especially along the steep outer slopes of volcanic cones (Mann et al., 2003; Mieth and Bork, 2005, 2018), local preservation at Pōike (Mieth and Bork, 2005) and Ma'uŋa Orito (Stevenson et al., 2006) reveals a once relatively fertile landscape from residual andesite soils. However, the island's soils are considered relatively impoverished due to the age of the volcanic parent material and rainfall levels resulting in heavily leached soils (Vitousek et al., 2004; Ladefoged et al., 2005, 2010; Louwagie et al., 2006). Attempts to increase the fertility of the soil, even to marginal levels, are suggested for intensively mapped rock gardens (also referred to as lithic mulching) (Stevenson and Haoa Cardinali, 1998; Stevenson et al., 2002).

Today the north and west inner region of Rano Raraku experiences extensive sheet and gully erosion. The lake covers approximately 11 ha including a marsh around its margins and an intermittent cover of floating reeds (Scirpus sp.; *totora*). Coring studies (Flenley et al., 1991; Baker, 1993; Dumont et al., 1998; Azizi and Flenley, 2008; Mann et al., 2008; Sáez et al., 2009; Horrocks et al., 2012a; Cañellas-Boltà et al., 2013) do not agree in all details but do show that the lake was present for the last 35ky, averaging 3 m deep with minor fluctuations and low levels during the mid-late Holocene. Lake level was confirmed at 2.9 m deep overall by sidescan radar during excavation of 156, although in an unusual event in 2018 it was dry for several months.

2.2. Rano Raraku culture history and archaeology overview

The proliferation, morphological similarity, and distribution of *moai* are indicative of task management and supervision, time investment, and craft specialization. The exclusivity of Rano Raraku tuff use in *moai* production establishes ritualization of the stone and, by extension, allows conceptualization of the place itself as sacred. The numbers and sizes of *moai*, including those remaining in the quarries, point to statue carvers as a non-subsistence producing elite group (*sensu* Earle, 1987; Brumfield and Earle, 1987). Others with lesser expertise (e.g., apprentice carvers) likely performed lower-level tasks, possibly extending to basaltic stone tool production (Simpson, Jr. et al., 2018). Interactions between *moai* artisans (*taŋata maori aŋa moai ma'ea*) and chiefly patrons conjecturally began with the paramount chief (*ariki mau*) and his direct line of descent (*ariki paka*) in cooperation with the highest-ranking priests (*ivi atua*). Ethnographic and ethnohistoric sources report subleadership ranks formed of chiefly advisors (*hōnui*) (Routledge, 1919:224; Métraux, 1940; Englert, 1974, 1978). This general pattern of cooperative/competitive social and economic interaction is well-documented for stateless societies (Stanish, 2017) including Polynesian (Kirch et al., 2011; Kirch et al., 2012) and a version of it is suggested for Rapa Nui agricultural field management (Stevenson and Haoa Cardinali, 1998; Stevenson et al., 2006).

The 1914-15 Mana Expedition to Easter Island mapped the shape and contours of Rano Raraku and marked the location of many statues on the inner and outer slopes (Routledge, 1919; Van Tilburg, 2003). The first controlled excavations in Rano Raraku using methods modern for the time were by Skjølsvold (1961). Hypothetical *moai* production methods were based on observations of Rano Raraku statues attached to bedrock (Routledge, 1919; Skjølsvold, 1961; Mulloy, 1970). Aerial photography and photogrammetry have facilitated survey of the outer slopes and quarries and preliminary mapping of the inner region (Cristino and Vargas, 1980; Cristino et al., 1981; Vargas, 1988; Vargas et al., 2006). This work was followed by development of a detailed *moai* catalog for Rano Raraku augmented by current and historic photo surveys, field notes and new morphometric documentation (Van Tilburg and Arévalo P., 2014).

3. Methods and materials

3.1. Excavation methodology

Moai 156 (Fig. 3b) is stylistically late and 6.6 m tall. It was excavated to base (Fig. 3c) as twelve 1 m squares within 2–4 m of the statue (Figs. 4 and 5). Excavated sediments were passed through a 6 mm screen and artifacts were logged as either singular finds or within one of 1427 bags collected by square, depth and material while field documentation included descriptive metrics, sketches, observations and selected other visual media, including targeted photogrammetry. Lithostratigraphic units (zones) were designated in the profile during Phase 2, Season 2, April 2014 and described by Munsell color, texture (including clasts > coarse sand), structure, other pedogenic features and the nature of boundaries. Profiles were documented for all vertical excavation exposures but only Profiles 5 and 4 (Figs. 5 and 6) relating to *moai* 156 in squares 24, 27, 30 and 06 are discussed here. Three types of samples were collected from Profile 5 including bulk sediment samples (ca. 100 g), soil/sediment intact micromorphology blocks and a continuous vertical column for flotation from the sidewall of square 30, Profile 5. The column measured 20 × 40 cm and extended down to 430 cm below surface, collected by zones. Samples were floated using hand agitation in a large water basin and recovered as light and heavy fractions. The light fraction was targeted for radiocarbon samples having well-defined contexts.

3.2. Radiocarbon analysis

A total of 49 charcoal samples were submitted for taxonomic analyses to J. Huebert and G. Murakami (2018) resulting in the differentiation of 246 charcoal sub-samples producing 187 instances of identified taxa (76% of the total examined). Forty-six (94%) of the total samples were from *moai* 156 and all but one of them was collected below 200 cmbs; two samples were from 157 and one was from the *umu* (see below). Only short-lived species and young twig wood were selected for dating, thus resulting in 19 fragments (41.3%) of charred plant remains from *moai* 156 along with one from the *umu* 14C dated by Beta Analytic, Inc. Chronological questions of interest include the time frame for raising *moai* 156 and the application of secondary petroglyphs as well as the duration and periodicity of sediment accumulation in the immediate vicinity.

Calibration and a Bayesian analysis of 14C ages were performed using Oxcal v4.2.3 and the SHCAL13 atmospheric curve (Bronk Ramsey, 2009; Bronk Ramsey and Lee, 2013; Hogg et al., 2013). We developed a Bayesian model from the calibrated 14C dates to take advantage of stratigraphic information independent of radiocarbon dating results to produce precise chronologies for investigating defined problems (Bayliss et al., 2007; Bayliss, 2009; Bronk Ramsey, 2009; Hamilton and Krus, 2018). Modeled ranges are presented as rounded to the nearest five years. A model and individual dates are considered valid if they return an agreement index of 60 or higher. As a model, results are interpretative estimates that can change as new excavations are conducted and additional data are included.

3.3. Geoarchaeological analyses

Twenty-one bulk soil/sediment samples from Profile 5 (see below) were collected and divided using a Jones Riffle Splitter. One split was sent to Horrocks in New Zealand for microbotanical analysis and half retained for chemical analyses to further characterize the soil. Laboratory methods follow standard procedures (Soil Survey Laboratory Staff, 1992) - pH in 1:1 soil water mixture, P1 Weak Bray, and extractable bases Ca, Mg, K, and Na by NH4OAC buffered at pH 7. These allow for assessment of soil fertility. Cation exchange capacity (CEC) and base saturation are calculated based on the total of base cations (Ca, Mg, K, Na) available to plants within that soil. The concentrations of cations are influenced by soil acidity and therefore represent an integrated measure of the nutrients available to and needed by plants.

Among the key indicators of a soil's fertility is the level of phosphorous that assists with reconstructing agricultural land use in leached tropical and subtropical soils where low levels can significantly limit productivity (Louwagie and Langohr, 2002; Louwagie, 2003; Vitousek, 2004; Vitousek et al., 2004; Meyer et al., 2007). The method we used, Weak Bray, can produce higher numbers since it is a fluoride containing extractant and can include Al phosphates (Van Raij et al., 2009; noted in Ladefoged et al., 2005: 103), relative to Resin P results (more recently used in volcanic contexts, method Kuo and Sparks, 1996). This should be kept in mind when comparing these data to others in volcanic regions. However, with our neutral pH and high base CEC the difference in data derived from these techniques is likely minimal.

Micromorphological block samples were collected opportunistically as oriented intact blocks (ca. 10 cm square) cut from profiles. Nine

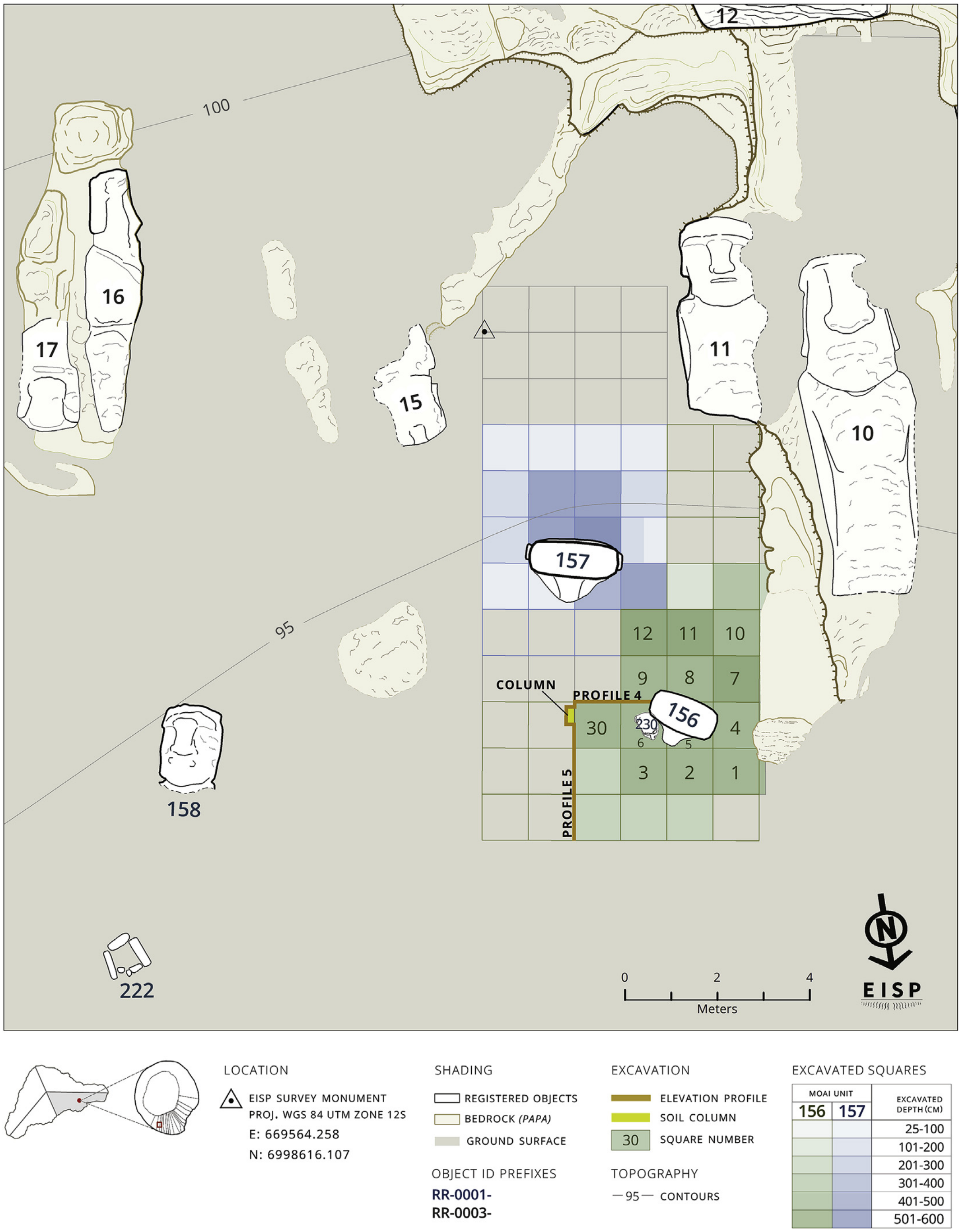


Fig. 4. Plan map, Quarry 2, Rano Raraku inner region: interlocking grid showing excavated squares (shaded); Profiles 4, 5, column excavation; upright *moai* (156 and 157; head 230; *umu pae* - 222) and other registered sculptural objects; ©EISP Archives and Database.

samples were collected from areas targeting clear stratigraphic contacts and localized lenses with concentrated anthropogenic sediments. Samples were shipped to the US where they were embedded in epoxy, cut and ground to 30 μm on large format (7.5 × 5 cm) slides by Spectrum Petrographics, Vancouver, Washington. Micromorphological analysis used magnifications ranging from 20 to 40x on a polarizing microscope under plane-polarized (PPL), cross-polarized (XPL), oblique incident (OIL) and fluorescent light (FL). This enabled observation of composition (mineral and organic), texture (size, sorting) and fabric (the geometric relationships among the constituents) of lenses observed during excavation (Courty et al., 1989; Stoops, 2003). These thin sections are analyzed to show specific attributes of the colluvium and possible surfaces within the deposits adjacent to *moai* 156.

3.4. Botanical

Macrobotanical samples were recovered from *moai* 156 excavation units and selected subsamples were analyzed by Huebert and Murakami (2018). Samples were recovered by excavation levels (later depths were assigned to zones) by *in situ* hand collection during screening and through flotation from the column excavated by zones noted above. Thirty-seven macrobotanical subsamples from the sediment column were submitted for identification; of these, 40.58% were unidentified or indeterminate (n = 28). Identified materials included 20.29% (n = 14) *Sophora toromiro* and 18.84% (n = 13) *Broussonetia papyrifera*. Wood identifications were performed by comparing anatomical characteristics of freshly fractured transverse and tangential facets with Pacific

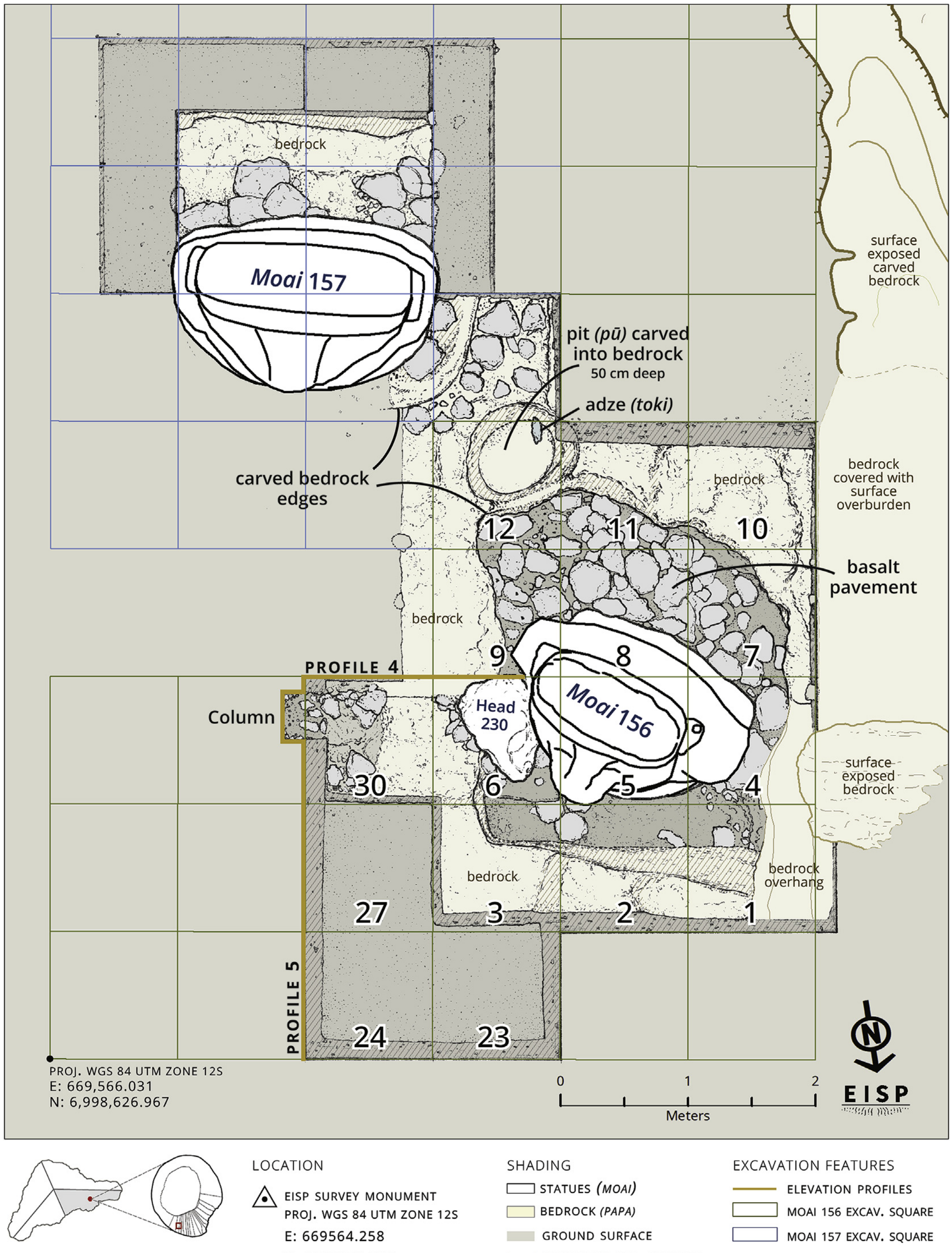
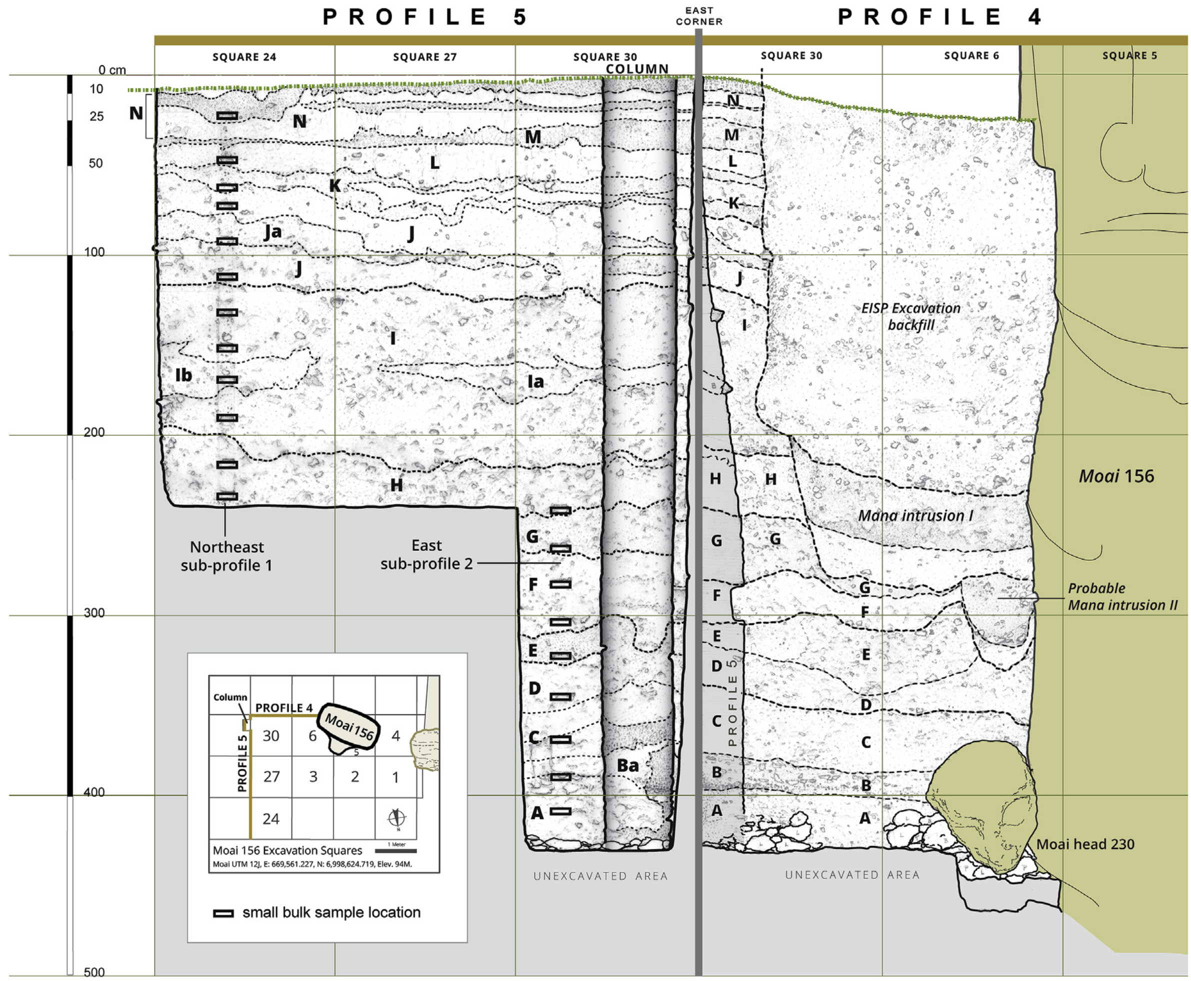


Fig. 5. Plan map of excavation floor and basal features including Head 230; Quarry 2, Rano Raraku inner region; ©EISP Archives and Database.

island woods in vouchered collections, University of Auckland and International Archaeological Research Institute, Inc.

The microbotanical analysis by Horrocks (2014) targeted pollen, phytoliths and starch from the 21 bulk samples described above. Pollen analysis included pollen grains of seed plants and spores of ferns and other plants. The samples were prepared by the standard acetylation method (Moore et al., 1991). Only the uppermost four samples contained enough pollen for meaningful counting. At least 200 pollen grains and spores, excluding undifferentiated types, were counted for three of these samples and slides were scanned for types not found during the counts. The sample from 55 cm depth contained less pollen, resulting in a count of 111 pollen grains and spores. For the remaining, pollen-poor samples, slides were scanned and occasional types noted.

The samples were prepared for phytolith analysis by density separation (Horrocks, 2005). At least 200 phytoliths, excluding undifferentiated types, were counted for each sample and slides were scanned for types not found during the counts. Other biogenic silica, in this case diatom and sponge spicule fragments, were not included in the counts from which the phytolith percentages were calculated, however, they are still expressed as a percentage of the base count. Starch grains and other plant micro-remains, such as xylem cells, were prepared for analysis by density separation and presence/absence noted.



Zone Descriptions Profiles 4 and 5

Surface: Dense grass.

N: Lenses of brown (10YR 4/3) silt loam; granular and crumb structure; dark yellowish brown (10YR 4/6) mottles.

M: Very dark gray (10YR 3/1) silt loam; fine granular structure; pebble-size mixed rock fragments.

L: Dense, yellowish brown (10YR 5/4) silt loam; aggregates of weathered brownish yellow (10YR 6/6) lapilli tuff; possible trachyte.

K: Very dark grayish brown (10YR 3/2) silt loam; aggregates of weathered dark yellowish brown (10YR 4/6) lapilli tuff; localized charcoal.

J: Layers of relatively dense, irregular lenses of yellowish brown (10YR 5/6) silty clay loam and dark grayish brown (10YR 4/2) loam; pebble to fine gravel-size lapilli tuff and possible trachyte; pebble-size beach cobble; common basalt debitage.

I: Dark Brown (7.5YR 3/2) silty clay loam; sub-rounded granule to pebble-sized lapilli tuff; charcoal fragments; basalt debitage.

Ia/b: Irregular lenses (10 – 20 cm thick, east profile) visible in middle of Stratum I. Yellowish brown (10YR5/48) clay loam; weathered lapilli.

H: Brownish yellow (10YR 6/6) clay loam; heterogeneous mix of weak red (10R 4/2) loam soil; granule and pebble-size sub-rounded lapilli tuff fragments; common basalt debitage.

G: Light gray (5Y 7/2) compacted loam; pebble to cobble-size lapilli; charcoal fragments.

F: Yellow brown (10YR 5/4) clay loam; lapilli fragments and granule-size basalt debitage.

E: Light gray (5Y 7/2) to light olive gray (5Y 6/2) loam; granule to pebble-size lapilli; cobble-size basalt fragments.

D: Dark grayish brown (10YR 4/2) clay loam to loam with common sand to granule-size charcoal fragments; many pebble-size lapilli; weak granular structure.

C: Dark gray (10YR 4/1) compressed clay loam; sand to granule-size charcoal fragments; granule to pebble-size lapilli; pebble-size basalt.

B: Dark gray (10YR 4/1) silty clay loam; gravel and pebble-size lapilli; basalt debitage.

Ba: Very dark brown (10YR 2/2) loam; common sand to granule-size charcoal fragments.

A: Loose, dark gray (10YR 4/1) clay loam; gravel-size yellowish to olive lapilli; abrupt irregular boundary over cobble-size unsorted lapilli. Fine silty clay clasts; charcoal fragments; sand-size fragments of reddish yellow (5YR 6/6) pigment; basalt boulders at statue base; upright, 70 cm tall carving of an anthropomorphic head (RR-0001-230).

Fig. 6. Profiles 4 (right) and 5 (left), *moai* 156: zone descriptions and bulk soil sample locations. Note Head 230 (right) at base of 156; illustration ©EISP Archives and Database.

4. Results

We discuss the results of this multidisciplinary project across several scales beginning with a focus on the stratigraphy to provide a framework in which to organize our analyses. The stratigraphy is further refined within the micromorphology and soil chemistry results. The macro and microbotanical data follow. Finally, the Bayesian statistical analyses model the timing and pace of the accumulation of sediments around *moai* 156, allowing us to consider changing land use practices in Rano Raraku inner region and the history of the upper portion of the quarry's colluvial slope.

4.1. Excavation stratigraphy results

Fig. 6 illustrates two adjoining profiles for *moai* 156 and the float column that best summarizes the results of the excavation. The overall stratigraphy was relatively homogeneous so differences in layers are subtle and typically consist of slight shifts in color and texture. Localized lenses of very dark gray (7.5YR 3/1) or dusky red (10R 3/3) sediment with charcoal and microartifacts were observed in profile and in the float column.

Stratigraphic zones are generally dark yellowish brown (10YR 4/4) silt loam to clay loam loosely consolidated with limited soil structure. The coarse fraction consists of variable concentrations of unsorted weathered gravel-size rock fragments. The non-artifact gravel-size clasts were predominantly tuff and small (< 5%) amounts of subangular fragments of basalt (likely part of the tuff bedrock). Clear, smooth zone boundaries suggest that these deposits do not represent a constant sediment accumulation but rather pulses of colluvium. These are likely produced during ground disturbance or increased sediment availability from statue production upslope or adjacent to the excavation area. This source area is limited within Quarry 2 and the colluvial sediment likely did not travel far.

Two groups of early 20th c intrusive deposits are clear in the profile. The deepest being probable Mana intrusion II (no zone label) and Mana intrusion I lies just below the EISP seasonal backfill (Labeled Zones R and Q) (Profile 4; Fig. 6). Routledge's field notes (Van Tilburg, 2003) briefly describe two episodes of digging and backfilling 156 (Routledge, 1919) to the level of what she called the “ring and girdle” design on the dorsal side, interpreted as a loincloth (*hami*) (González et al. 1988; Van Tilburg, 1988b). The relatively horizontal zones beyond the early 20th c disturbances are assumed to have continued laterally to the statue.

Artifacts were found throughout the profile but were more concentrated below Zone I. The most common were lithics, primarily basaltic and obsidian debitage, with basaltic material most concentrated from Zone B up through Zone J. A total of 262 finished, roughly flaked basaltic hand tools (*toki*), used in the quarrying process, were recovered in the *moai* 156 excavation units. Two separate studies, one using portable x-ray fluorescence (pXRF) of a sample of 168 complete *toki* (Fischer and Bahamondez, 2012), and a second study using geochemical and radiometric analyses (Simpson, Jr. et al., 2018), both sourced the basalt to a quarry area about 6 km from Rano Raraku. This may suggest *toki* production specialization, at least for Quarry 2. Other artifact types include a large, shaped piece (80 g) of red pigment (*ki'ea*), bone (including human and fish), a basaltic spear point (*matá*), a broken, one-piece jabbing type bone fishhook (*maŋai ivi*) and a large, squared-off coral block. Charcoal is common in the lower half of the section (up to Zone G) but is also found in low percentages in the upper half of the section.

Excavation in several squares continued to bedrock where *Moai* 156 is set firmly within a skillfully carved and polished bedrock feature which extends to encompass *moai* 157 (Figs. 3c and 5). Propped amidst the rubble and against the right side of 156 is a roughly carved tuff head and face sculpture (RR-0001-230; Figs. 3d, 5 and 6) in a style associated with the ritual site of ‘Oroŋo (Van Tilburg and Arévalo Pakarati, 2014: 176). Basal features included a 55 cm deep bedrock hole (*pū*) with a flat bottom and slightly sloping walls carved between the two statues (Figs. 3c and 5). Rim wear suggests use as a posthole.

4.1.1. Micromorphology results

The micromorphology analysis reveals a granular microstructure composed of aggregates in a silty clay matrix with vesicular volcanic glass of differing amounts of plagioclase, olivine, pyroxene and opaque oxides, all variably weathered and unsorted (Fig. 7a–c). A few distinct localized lenses were encountered below Zone G in square 30 and in the column excavation (Fig. 8a). These are thought to represent intact remnants of anthropogenic activities other than quarrying. One such anomaly was observed about 380 cm below the surface in Zone B (which includes a concentration of basalt flakes) and Zone C, composed of thin lenses of charcoal and dusky red (10R 3/4) sediment clasts (Fig. 8b). Captured in thin section this lens includes concentrated aggregates of charcoal, phytoliths, weathered tuff and calcareous ash (Fig. 8c–f). The red sediments and presence of ash suggest wood and grass burning and probable food processing. Different types of phytoliths are visible throughout the thin sections but articulated grass phytoliths are only observed in these ephemeral surfaces (Fig. 8e and f). The abundance of grasses (further represented in the microbotanical data) at the landscape scale supports at least intermittent slope stability through vegetation but their abundance in the lenses may be linked to cooking practices. The presence of silt and clay-sized clasts of graded bedding observed in thin section suggest areas of exposed sediment at the surface where water pooled under slack water conditions (Fig. 8g).

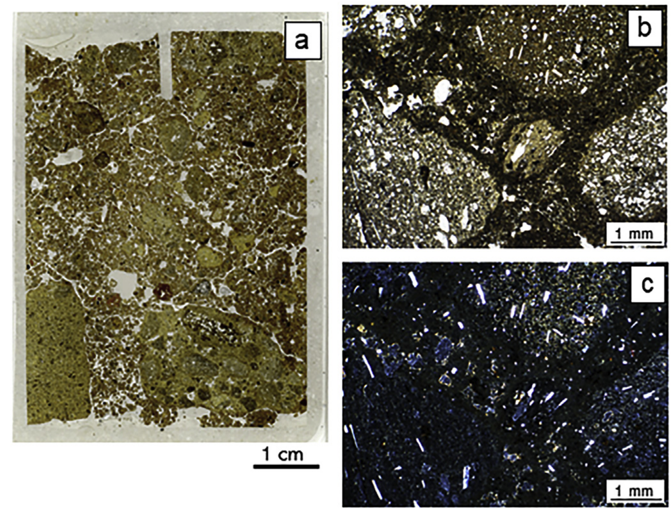


Fig. 7. Weathered lapilli tuff (quarried material) captured in thin section, Zone F; a) Typical matrix with weathered lapilli in scanned thin section; b) photomicrograph of weathered lapilli tuff (PPL); c) same view (XPL). (sample 14EI03, Sq 2, 260 cmbs).

The thin sections observed outside the ephemeral surfaces revealed diagenetic weathering, e.g., bright orange palagonitized rims in volcanic glass vesicles (Fig. 8h and i). However, there was no macro or micro evidence for a buried soil or horizonation in the excavation profile. The absence of defined horizons, coupled with the relatively uniform by depth chemical data (see below), support rapid sediment accumulation. Also absent in thin section are features related to the downward movement of fines such as cappings, infilled voids or bridging of clasts or grains.

4.1.2. Soil chemistry results

The bulk sediment chemical analyses indicate remarkably fertile soil for a dryland volcanic context (Table 1). These data reveal nutrient levels higher on average than any of the garden contexts sampled elsewhere on the island (e.g. Ladefoged et al., 2005, 2010; Stevenson et al., 2002, 2015, 2018). Throughout the profile, especially deeper than 2 m, the data reveal favorable slightly alkaline pH conditions (m = 7.69) and high available P (m = 82.7 mg/kg). Phosphorus levels are lowest in the upper 40 cm measuring around 50 mg/kg but they increase quickly with depth and average 92 mg/kg below 2 m. The base CEC averages m = 38.1, suggesting the soil has abundant positively charged ions which influence soil structure stability and nutrient availability, crucial properties for plant health and productivity. The sum of exchangeable cations (Ca, Mg, K, Al) is dominated by calcium indicating the potential for abundant yields among cultivars (see discussion) (see Table 1).

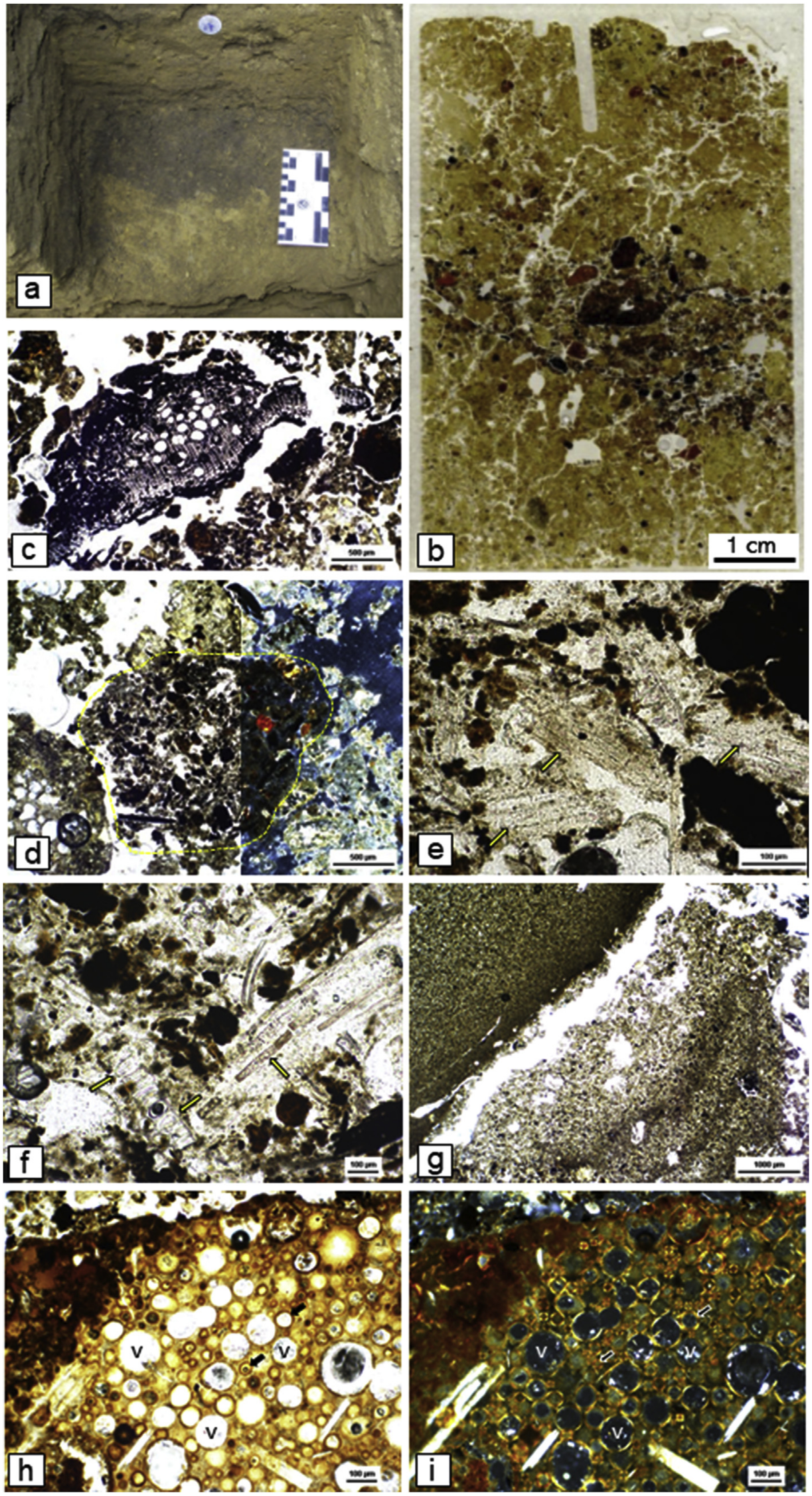


Fig. 8. a) photo in the field of a localized lens of charcoal and red sediment in Zone C, (float column, similar to the one cross-cut by sample 14EI08 in b) scan of thin section 14EI08 cross-cutting localized lens (sample 14EI08, Zone B); c) photomicrograph of wood charcoal fragment, possibly bark (PPL); d) photomicrograph of charcoal and ash aggregate, outlined in yellow dashed line (left PPL, right same view XPL) in a matrix of weathered lapilli tuff grains; e & f) photomicrographs of different types of concentrated phytoliths (PPL), yellow arrows point at examples of phytoliths; g) photomicrograph graded bedding (PPL); h) photomicrographs of bright orange palagonitized rims (examples marked with black arrows) weathering in volcanic glass vesicles (examples marked with "v" (PPL); i) same view as h) XPL.

While P is typically the least mobile among soil elements, the range in levels has been correlated with greater rainfall, parent material and soil age. If we consider these factors relatively consistent across the few hundred years it took this sequence to accumulate, noting the highest P results are derived from 285 to 360 cm in an area of incipient surfaces, then human activity is likely the primary contributor to these higher P levels. Based on the range of the macroartifacts recovered and the anthropogenic sediments in thin section, activities likely included food

Table 1
Soil chemistry results from Rano Raraku, Unit 156.

cm below surface	Zone	pH	P1 mg/kg	Ca mg/kg	Ca base Saturation	Mg mg/kg	Mg base saturation	K mg/kg	K base saturation	Na mg/kg	Na base saturation	CEC
15	N	6.84	52	3890	48.75	2080	43.44	1020	6.56	115	1.25	39.8987
40	L	6.86	48	4370	58.48	1220	27.21	1790	12.28	174	2.02	37.3629
55	K	6.94	73	4720	55.35	1960	38.31	812	4.88	143	1.46	42.6371
65	J	6.95	71	4420	54.47	1810	37.18	1000	6.32	190	2.04	40.5735
85	Ja	6.91	75	3310	55.38	1180	32.90	1100	9.44	157	2.28	29.8865
105	J	7.20	74	4200	59.78	1240	29.42	1200	8.76	165	2.04	35.1276
125	I	7.13	82	3320	59.37	976	29.09	1030	9.45	135	2.10	27.9613
145	I	7.39	74	3290	59.72	915	27.68	1120	10.43	138	2.18	27.5468
165	Ib	7.48	85	3550	59.92	1010	28.41	1130	9.78	128	1.88	29.6206
185	I	7.57	88	4010	59.42	1090	26.92	1530	11.63	158	2.04	33.7434
205	H	7.70	98	4150	59.46	1140	27.22	1550	11.39	155	1.93	34.8983
225	H	7.68	93	4100	49.35	2200	44.13	828	5.11	135	1.41	41.5434
245	H	7.60	97	3120	58.05	948	29.39	1040	9.92	163	2.64	26.8754
265	G	7.63	94	4330	56.65	1420	30.97	1460	9.80	227	2.58	38.2139
285	F	7.44	103	4540	54.54	1660	33.24	1580	9.73	238	2.49	41.6194
305	F	7.77	88	5510	55.08	1910	31.82	2030	10.41	309	2.69	50.0153
340	E	7.41	98	5150	54.52	1840	32.46	1920	10.42	282	2.60	47.2325
360	D	7.80	112	5000	54.88	1900	34.76	1470	8.27	218	2.08	45.5504
390	C	8.02	84	3850	53.08	1580	36.30	1200	8.48	178	2.13	36.2675
410	A	7.77	78	5190	52.57	2050	34.61	1990	10.34	282	2.48	49.3620
430	A	7.82	70	4470	50.34	1970	36.97	1760	10.16	258	2.53	44.4012

preparation, especially cooking. Other possible actions could include bringing detritus from the marsh to enhance soil conditions for farming. In sum, high indicators of soil fertility are relatively consistent throughout the profile.

4.2. Macrobotanical results

Macrofossil results include *Broussonetia papyrifera* (paper mulberry; *mahute*), *Cordyline fruticosa* (Tī), *Thespesia populnea* (Pacific rosewood; *mako'i*) and *Ipomoea batatas* (sweet potato; *kumara*) (Huebert and Murakami, 2018 (Supplementary Tables 1 and 2). In addition to introduced cultivars, elements of indigenous woody and herbaceous vegetation were present in the study area. Taxa recovered as charcoal include *Sophora toromiro*, large and small grass stems (Poaceae) and wood fragments from large palms (Arecaceae) and others. The microfossil assemblage compliments these findings by providing another line of evidence for all the native taxa, as well as additional information on grasses, sedges, ferns, hornworts and others.

4.3. Microbotanical results

4.3.1. Pollen results

The pollen assemblage of the uppermost 65 cm were the only samples with sufficient pollen for analysis and it was dominated by grasses (Poaceae) and sedges (Cyperaceae) (Fig. 9). Hornwort (Anthocerotopsida) spores are present, but trees and shrubs are represented by negligible amounts of toromiro (*Sophora toromiro*) and (*Triumfetta*) pollen. Other tree and shrub pollen types, namely Asteraceae, palms (Arecaceae) and Moraceae/Urticaceae, appear in the uppermost two samples at 40 and 15 cm depths.

Pollen of a post-contact taxon, namely Cheno-Am (Chenopodiaceae and/or Amaranthaceae, the pollen of which is difficult to differentiate), appears at 40 cm depth (Fig. 9). Cichorieae pollen also appears at this depth. The Cheno-Am pollen indicates post-contact activity. The Cichorieae pollen, also found at this depth, could likewise be from introduced post-contact plants. Flenley et al. (1991) suggested that prehistoric species of this sub-tribe of plants likely include the invasive herbs *Sonchus asper* and *S. oleraceus*. Its apparent absence in pre-settlement Rapa Nui deposits suggests it was a Polynesian introduction, perhaps accidental. *Sonchus*, however, could have been a pre-Captain Cook European introduction to the Pacific islands (Arthur Whistler, pers. commun.). The Cichorieae pollen in this case could also be from species introduced post Western contact, such as dandelion (*Taraxacum officinale*). Pollen types found in the pollen-poor samples (below 65 cm) comprise mostly grasses and hornworts. Moraceae/Urticaceae pollen was found in the sample from 390 cm depth (Fig. 10a).

4.3.2. Phytolith and starch results

Phytoliths, many of which were fragmented, are preserved in large quantities in all samples. The phytolith assemblages throughout the profile are dominated by palms (up to > 70%) and grasses (up to > 35%) and to a lesser extent totora (*Scirpus californicus*) (Fig. 11). The latter has larger amounts in the broad central part of the profile. Small amounts of phytoliths of banana (*Musa* sp.) leaves and paper mulberry (*Broussonetia papyrifera*) leaf hairs (present as short hooked hairs and fragmented long wavy hairs) were found throughout most of the profile (Fig. 10b and c; 11). Moraceae/Urticaceae pollen was identified in the samples from 390 to 40 cm depths. While pollen of the Moraceae family, to which paper mulberry belongs, is difficult to distinguish from that of another plant family, the Urticaceae, given that paper mulberry phytoliths were found in the vast majority of the samples, the pollen is likely from the paper mulberry taxon. The banana phytoliths were present as individuals and occasionally linear chains (Fig. 10d). Biogenic silica other than phytoliths, in this case notably diatom fragments (also noted in the micromorphology), were found throughout most of the profile.

None of the samples contained convincing evidence of starch or associated microscopic plant material. All the profile samples have abundant microscopic fragments of charcoal, which is similar to the soil profile on the northern slope of the basin, where charcoal was found throughout the full soil profile (Horrocks et al., 2012a).

4.3.3. Microbotanical taphonomic considerations

Microbotanical remains have the potential to be significantly impacted by certain taphonomic processes that must be taken into consideration as we interpret the pollen and phytolith data. Sweet potato and taro are pollinated through entomophily which leads to low pollen concentrations. Further, Faegri et al. (1989) and Haberle and Atkin (2005) have demonstrated the susceptibility of sweet potato pollen exine to physical and chemical degradation compounding poor preservation. The poor pollen preservation below 65 cm depth in the profile in part reflects the older age of the relevant deposits as well as the high pH.

The preservation of abundant phytoliths, both fragmented and

Table 2
Radiocarbon ages and details of samples collected from the excavation and used in the analysis.

Context (Unit-Square-Zone)	Depth (cmbs)	Taxa ID	Common Name	Lab No	Radiocarbon Age (BP)	$\delta^{13}C$ (0/00)	Material Notes
156-30-B/C	328–395	*Ipomoea batatas*	Kumara	Beta-447618	350 ± 30	−21.2	charred tuber
156-30-B/C	328–395	*Indeterminate hardwood*		Beta-410767	390 ± 30	−25.2	wood charcoal; twig 5 mm dia. With pith
156-30-B/C	328–395	*Indeterminate hardwood*		Beta-410768	280 ± 30	−26.5	wood charcoal; twig 3 mm dia. With thin bark, hollow
156-06-D/E/F	280–330	cf. *Broussonetia papyrifera*	paper mulberry	Beta-410634	380 ± 30	−25.7	wood charcoal
156-05-G	325	*Indeterminate hardwood*		Beta-410769	220 ± 30	−25.6	wood charcoal; twig 4 mm dia. With thin bark, hollow
156-05-B/C	334–380	*Indeterminate hardwood*		Beta-410770	390 ± 30	−26.0	wood charcoal; twig 8 mm dia. Hollow
156-02-D/E/F	250–322	cf. *Broussonetia papyrifera*	paper mulberry	Beta-410635	400 ± 30	−25.7	wood charcoal
156-05-F/G	325–371	*Indeterminate hardwood*		Beta-410771	370 ± 30	−28.1	wood charcoal; hollow twig, 5 mm dia.
156-04-D	300–310	cf. *Broussonetia papyrifera*	paper mulberry	Beta-410636	370 ± 30	−26.1	wood charcoal
156-03-C2	363–420	cf. *Broussonetia papyrifera*	paper mulberry	Beta-410637	360 ± 30	−25.9	wood charcoal
156–01	330–412	cf. *Broussonetia papyrifera*	paper mulberry	Beta-410638	380 ± 30	−26.9	wood charcoal
156-30Col-B2	397	*Broussonetia papyrifera*	paper mulberry	Beta-412398	360 ± 30	−26.6	wood charcoal; juvenile wood
156-30Col-B1	364–380	*Broussonetia papyrifera*	paper mulberry	Beta-412399	240 ± 30	−25.5	wood charcoal
222–00	0–50	*Indeterminate hardwood*		Beta-410772	100 ± 30	−27.8	wood charcoal; curved portion of twig ~8 mm dia., thin bark, radial fissures
156-09-A	434–496	*Indeterminate hardwood*		Beta-410773	340 ± 30	−26.0	wood charcoal; curved portion of twig ~6 mm dia., thin bark
156-08- A	420	cf. *Broussonetia papyrifera*	paper mulberry	Beta-410774	90 ± 30	−26.6	wood charcoal
156-30Col-C	325–341	*Broussonetia papyrifera*	paper mulberry	Beta-412400	260 ± 30	−25.1	wood charcoal; portion of ~1 cm dia. Twig with pith
156-30Col-D	280–300	*Broussonetia papyrifera*	paper mulberry	Beta-412401	260 ± 30	−25.6	wood charcoal; 7 mm dia. Twig with pith
156-30Col-F	250–280	*Broussonetia papyrifera*	paper mulberry	Beta-412402	150 ± 30	−24.2	wood charcoal
156-30Col-G	212–230	*Broussonetia papyrifera*	paper mulberry	Beta-412403	50 ± 30	−26.2	wood charcoal; 5 mm dia. Twig with pith

whole, to the full depth of the profile, in contrast to the pollen, reflects their inorganic composition whereby they resist decomposition by soil micro-organisms. The large to very large amounts of palm phytoliths throughout the entire profile could seem at odds with the coincident low pollen values for this taxon (Fig. 11). However, these amounts most likely reflect the over-representation of palms in the Easter Island phytolith spectra (Cummings, 1998), with other trees and ferns poorly represented, exacerbated by pre-clearance palm phytoliths accumulating in largely remobilized deposits. Palm phytoliths can also be recycled in plants like sweet potatoes (Tromp and Dudgeon, 2015), further adding to their preservation in post palm clearance contexts.

4.4. Bayesian modeling results

The spatial contexts of the organic materials submitted for radiocarbon dating were used to inform the building and inspection of a Bayesian model to better refine the chronology of activities that generated over 4 m of sediment in Quarry 2, nearly burying *moai* 156. Twenty selected samples were recovered from excavated matrices in squares 1–6, 8–9, 30 and the associated cooking place (Fea. 222; *umu* or *umu pae*; stone-lined earth oven) located approx. 10 m northeast of the excavation (Table 2; Fig. 4). We divided the dates into three groups. The first includes 13 samples recovered during dry sifting. These levels in some cases are relatively thick and cross more than one zone; they are not assumed to reflect vertical stratigraphic relationships in this analysis. The second group consists of six dates from samples collected from the float column associated with square 30. These have known vertical depths directly linked to stratigraphically ordered zones. The third group is a single sample from the *umu* (Fea. 222; Beta-410772) (Van Tilburg and Arévalo Pakarati, 2014: 26), which intrudes the current surface indicating its periodic use for traditional food preparation when today's slope was stable. That date is therefore assumed to post-date the formation of all other dated contexts.

The model treats these three groups of radiocarbon data within three uniform phases that are ordered sequentially and assumes two separate periods of deposition occurred prior to slope stabilization and use of the intrusive *umu* (Fig. 12). Prior information drawn from the known stratigraphic relationships, geoarchaeological analysis, and the concentration of petroglyphs and visible patterns of variable surface weathering allow us to order the three phases this way. The initial phase (Fig. 12: Phase quarry activity 1) is populated by 18 dates followed by two phases that are both informed by single dates. The initial phase includes a sequence (Fig. 12: *Sequence column*) composed of five of the six dates taken from the vertical column. These five dates are ordered stratigraphically – that is, samples from lower column strata are assumed to date zones that formed prior to being capped by overlying strata. This 5-date sequence is modeled inside this first phase, meaning that the grouped sequence could fall at any time within the parent phase. Undated start and end boundaries are modeled for the initial phase, useful for estimating the phase length and span. The second and third phases are modeled sequentially to follow the end of our first phase. The second phase (Fig. 12: Phase quarry activity 2) is informed by the uppermost radiocarbon date from the vertical column (Zone H) and is based on the correlation of stratigraphic zones, petroglyph cluster elevations and the visible changes in weathering on the dorsal side of the statue (Figs. 3b and 13). The placement of the petroglyphs concentrates into an upper group suggesting the lower portion of the statue was unavailable at the time of their production. This further suggests that Zones B through G accumulated as activity continued in the vicinity, with Zone H representing a cessation of quarrying in Quarry 2. We propose that it also represents a shift in land use within Rano Raraku.

This model fits well with the data (A_{model} = 102)[1]. We suggest that Zone A may have remained stable, even perhaps maintained, with the recent rising of *moai* 156. Sample 412398, collected from the top of Zone A, near its interface with Zone B, provides the closest estimate for

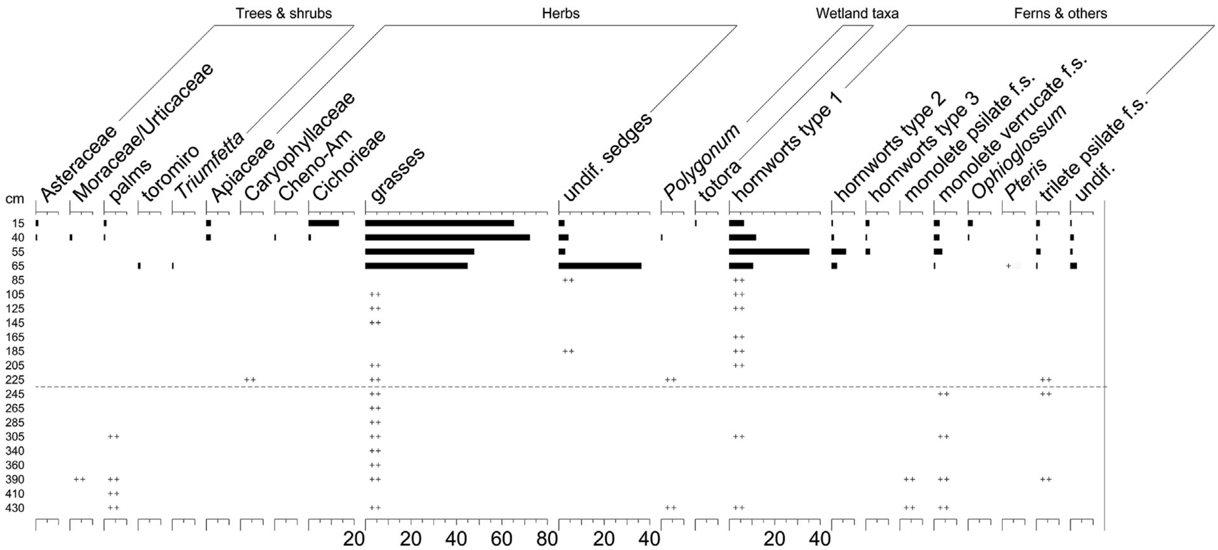


Fig. 9. Pollen diagram by depth. + = found after count, + + = present. Bulk samples from Profile 5, sq. 24, 30 (see Fig. 6).

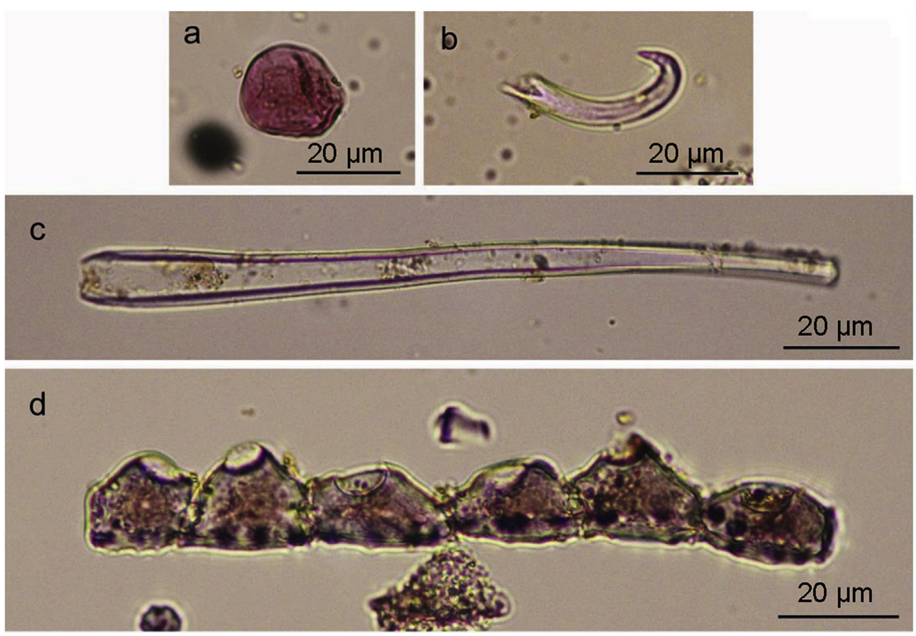


Fig. 10. a) Paper mulberry (Moraceae/Urticaceae) pollen grain, 600x; b) Short hooked paper mulberry leaf hair phytolith, 600x; c) Long wavy paper mulberry leaf hair phytolith, with tip broken off, 400x; d) Chain of six banana (*Musa*) leaf phytoliths, 600x. All scale bars: 20 μm.

the rising of this *moai* sometime before *cal AD 1510-1645* (*95% probability*) (Fig. 14a). Based on our interpretation illustrated in Fig. 13 the model assumes a phase of activity in Rano Raraku Quarry 2 starting in *cal AD 1455-1605* (*95% probability*), probably in *cal AD 1495-1585* (*68% probability*; Fig. 14b) and ending in *cal AD 1665-1750* (*95% probability)*, probably in *cal AD 1675-1710* (*68% probability*; Fig. 14c). This phase is estimated to have lasted for *250–470 years* (*95% probability)* but probably for *315–425* years (*68% probability*; Fig. 14d). *Moai* 156 was raised in place just prior to this time or at the start and likely became a focus of localized ritual. This accumulation and active slope were punctuated with brief events that occurred near the statue, suggested by the micromorphology results. After this phase additional deposition occurred, resulting in Zones I through J. We consider Sample 413403 from Zone H a suitable proxy for the start of this second phase of deposition (see Bayliss et al., 2011: 25) and estimate it beginning by *cal AD 1805-1925* (*87% probability*), but likely by *cal AD 1810-1835* (*47% probability*) or *cal AD 1890-1910* (*21% probability*; Fig. 14e), well into the historic period. This second phase appears to represent the slow but constant rate of sediment accumulation, likely due to upslope erosion, after quarrying had ceased. Zone I is relatively homogeneous suggesting probable continuous accumulation and pass through without obvious pulses or the presence of incipient surfaces. We suggest this represents a significant change in land use or agricultural practice. The upper 75 cm + of the profile, above Zone J, is heavily influenced by historic activity in the area including intensive sheep grazing, periodic on-site food preparation evidenced by the *umu* feature (Fig. 14f) and subsequent exploratory digging. These upper-most contexts were too compromised to radiocarbon date, so we merely estimate this accumulation to have occurred during the late 19th and early 20th centuries.

5. Discussion

Here we discuss two overarching topics on which the excavation

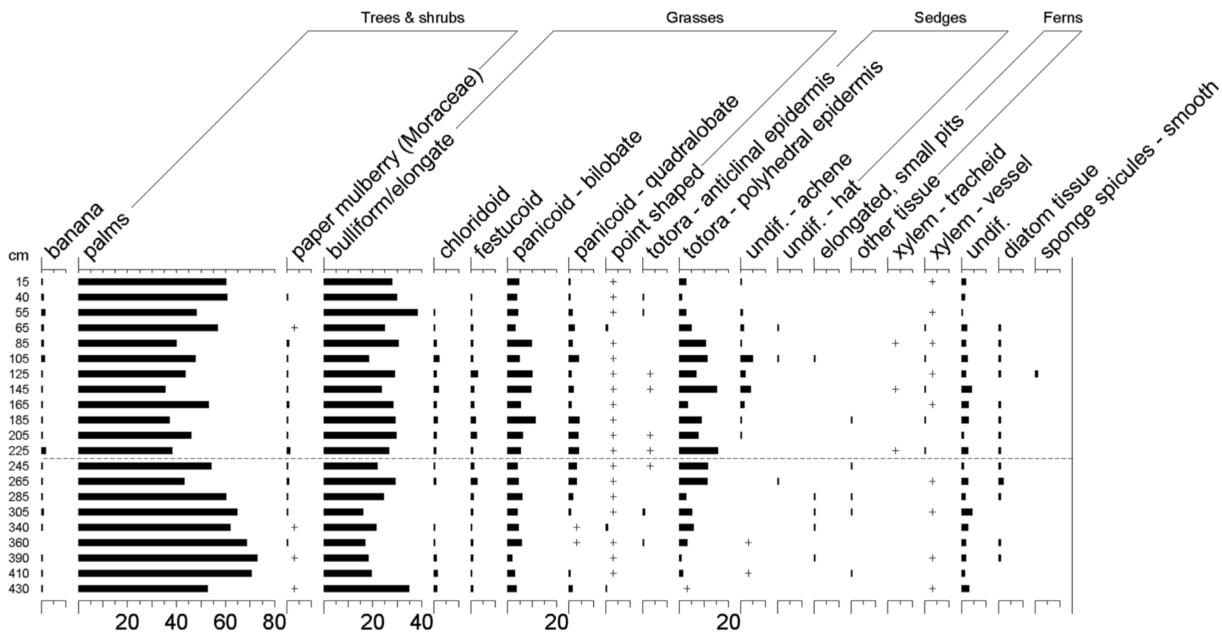


Fig. 11. Phytolith diagram by depth. + = found after count. Bulk samples from Profile 5, sq. 24, 30 (see Fig. 6).

data provide direct insights into human use of the Rano Raraku inner region from the 15th century to the beginning of the 20th century. An island-wide socio-political shift followed a population rise from ca. AD 1400–1650 (Flenley and King, 1984) as indicated in the number and distribution of radiocarbon results (Mulrooney, 2013) and perhaps peaking in the 17th century (Louwagie et al., 2006) as marked by apparent changing settlement patterns and proxy evidence for climate fluctuations. A rise in *taŋata manu* rituals at ʻOroŋo is conjecturally concomitant with the slowing to termination of *moai* production (Métraux, 1940; Routledge, 1919; Englert, 1978; Van Tilburg and Arévalo Pakarati, 2009, 1994; Vargas, 1988; Orliac and Orliac, 1996; Stevenson et al., 2006; Vargas et al., 2006; Mulrooney, 2013; Robinson and Stevenson, 2017). Following evidence of agricultural intensification but in sharp contrast to hypothesized diminished production, Rano Raraku inner region soils could produce high agricultural yields and when combined with ample local availability of water, required minimal labor investment. Here we discuss the potential for agricultural productivity based on soil fertility and then the macro and microfossil evidence, followed by the timing of suggested adaptive reuse of *moai* 156 in ritual activities.

5.1. Agriculture in Rano Raraku

Intensive dryland farming of bananas, taro, and especially sweet potato was the primary source of subsistence on Rapa Nui prior to European contact (Wallin et al., 2005; Louwagie et al., 2006; Louwagie and Langohr, 2007). As shade gardening shifted to dryland farming with the decline and ultimate loss of forest cover, localized soil erosion and depleted soil quality emerged. This problem is not unique to Rapa Nui as loss of soil fertility is common in shallow volcanic soils and the "old garden effect" (*sensu* Walter et al., 2011) requires careful and innovative management, or abandonment. Pre-contact Pacific Island cultures are known for food production and surplus storage in excess of immediate sustenance needs in response to well-developed social and ritual demands (Farrell, 1972; Kuhlken, 2002). Therefore, understanding how Rapa Nui navigated a reduction in soil fertility within existing environmental constraints (e.g., leached volcanic soils, loss of forest resources, limited fresh water, absence of marine shallows, etc.) with the necessity to feed a growing population, has become an important question. Researchers have focused on innovative ways in which gardens were constructed over much of the island and how they may have retained moisture or introduced new soil nutrients and their potential to provide reliable, even surplus yields in such a risk laden agricultural system (Stevenson and Haoa Cardinali, 1998; Wozniak, 1998, 1999; 2003; Stevenson et al., 1999, 2002; 2006; Ladefoged et al., 2005; Louwagie et al., 2006; Louwagie and Langohr, 2007; Baer et al., 2008; Horrocks and Wozniak, 2008; Vitousek et al., 2014).

Key studies emanating from the Hawai'i Biocomplexity Project (Ladefoged et al., 2003; Vitousek et al., 2004, 2014; Ladefoged and Graves, 2008; Kirch et al., 2011) investigate intensive dryland agriculture in a few of the Pacific Islands (e.g., Hawai'i, Maui, Rapa Nui) and provide soil biogeochemical nutrient data on which to compare our results from Rano Raraku. Their studies show that agricultural landscapes that succeed in a rainfed intensive system are principally constrained by substrate and rainfall (e.g., Vitousek et al., 2004, 2014; Baer et al., 2015; Stevenson et al., 2018). The project emphasized elevation linked to precipitation and soil nutrients available through volcanic rock weathering (age of the substrate) and from their data, specifically from the Leeward Kohala Field System on the island of Hawai'i, chemical thresholds were identified that highly correlate with successful intensive dryland systems (Ladefoged and Graves, 2000; Chadwick et al., 2003; Ladefoged et al., 2005, 2010). The most informative thresholds, comparable to our data from Rano Raraku, are pH with a threshold of 5.7, resin-extractable P $>$ 25 μg/g, available Ca (Ca^{++}) with a threshold of $>$ 10.2 meq/100 g and base saturation with a threshold of $>$ 30% (Ladefoged and Graves, 2000; Ladefoged et al., 2003; Kirch et al., 2004; Vitousek, 2004).

Fig. 15 illustrates the Rano Raraku data in relation to the thresholds for pH, exchangeable Ca, and P. The Rano Raraku excavation produced soil data above the thresholds throughout the entire Rano Raraku profile. These data are also above any produced for the Rapa Nui rock gardens where the upper agriculturally active soils are significantly leached compared to the deeper parent material (e.g. Louwagie and Langohr, 2002; Ladefoged et al., 2005, 2010; Stevenson et al., 2002, 2018). In short, Rano Raraku inner region soils had the potential to produce significantly higher yields with considerably lower labor costs than did the various types of rock gardens (described in Baer et al., 2008) which are estimated to have been the dominant agricultural practice in the last few centuries prior to and after European contact (Stevenson and Haoa Cardinali, 1998; Stevenson et al., 1999, 2002;

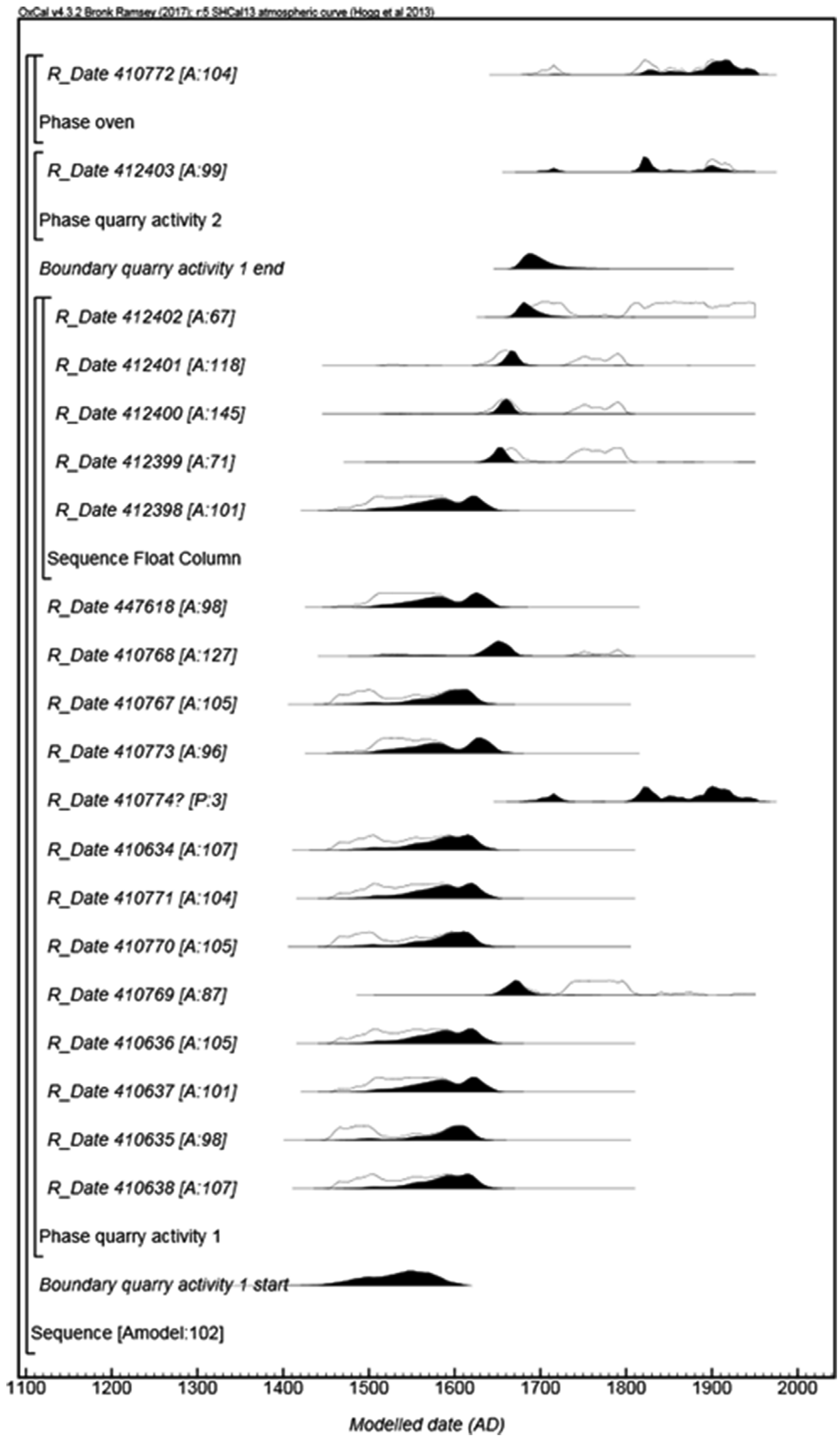


Fig. 12. Radiocarbon calibration and Bayesian Multiplot Model based on analysis of twenty14C ages. Oxcal v4.2.3 using the SHCAL13 atmospheric curve (Bronk Ramsey, 2009; Bronk Ramsey and Lee, 2013; Hogg et al., 2013).

Louwagie et al., 2006; Ladefoged et al., 2010). While our base CEC results are high (Table 1) a high base saturation with the alkaline pH values is presumed but cannot directly be calculated and compared to that of the Hawai'i Biocomplexity Project thresholds without measurements for the exchangeable Al and H. The base CEC for the EISP excavation is high throughout the profile with a mean of 36.38.

Fig. 15 also graphs the data collected for the full 420 cmbs profile. Most of the comparative data from the rock garden studies and those in other dryland contexts are derived from the upper 30 cm, further illustrating the extent of high nutrients within the inner region of the *moai* quarry, extending over several centuries. With the relatively constant influx of “new” parent material and anthropogenic input, soil

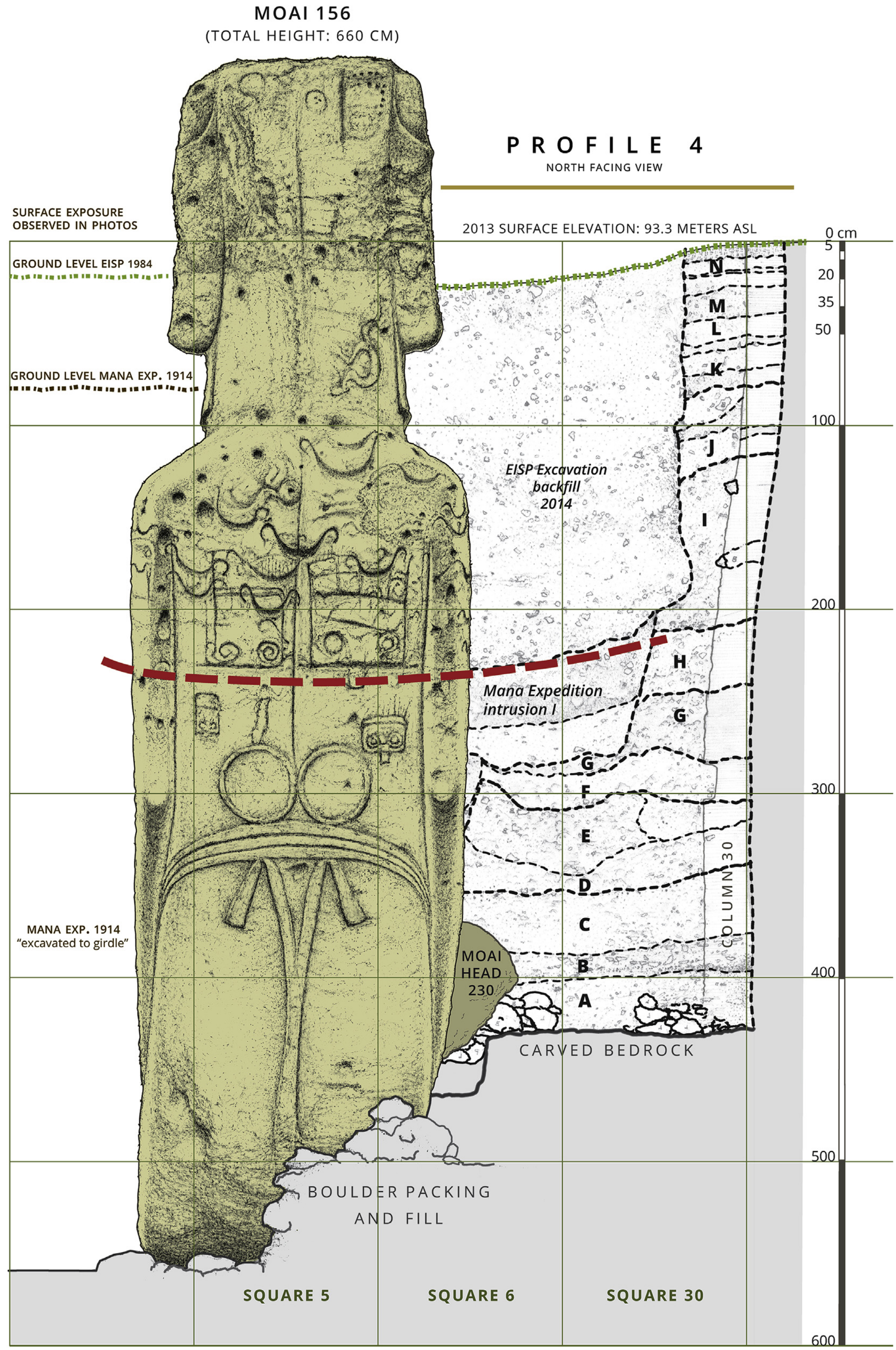


Fig. 13. Profile 4 relative to *moai* 156: red dashed line represents the estimated surface when the area was stable temporarily and petroglyphs were applied. This is the proposed upper limit of active quarrying and modeled as Phase Zone H; *moai* illustration Cristián Arévalo Pakarati; ©EISP Archives and Database.

fertility is high throughout the sequence, especially in the lower half. Below 2 m the profile reveals high exchangeable Ca, thus indicating the inverse to most stable volcanic soils where typical weathering in tropical and subtropical conditions results in cation depletion (e.g., Lincoln et al., 2014).

Potassium is an especially essential element in the productivity of sweet potatoes (Byju and George, 2004). Studies of volcanic soils in New Guinea indicate a range of 17.7–352.4 mg/kg exchangeable K and

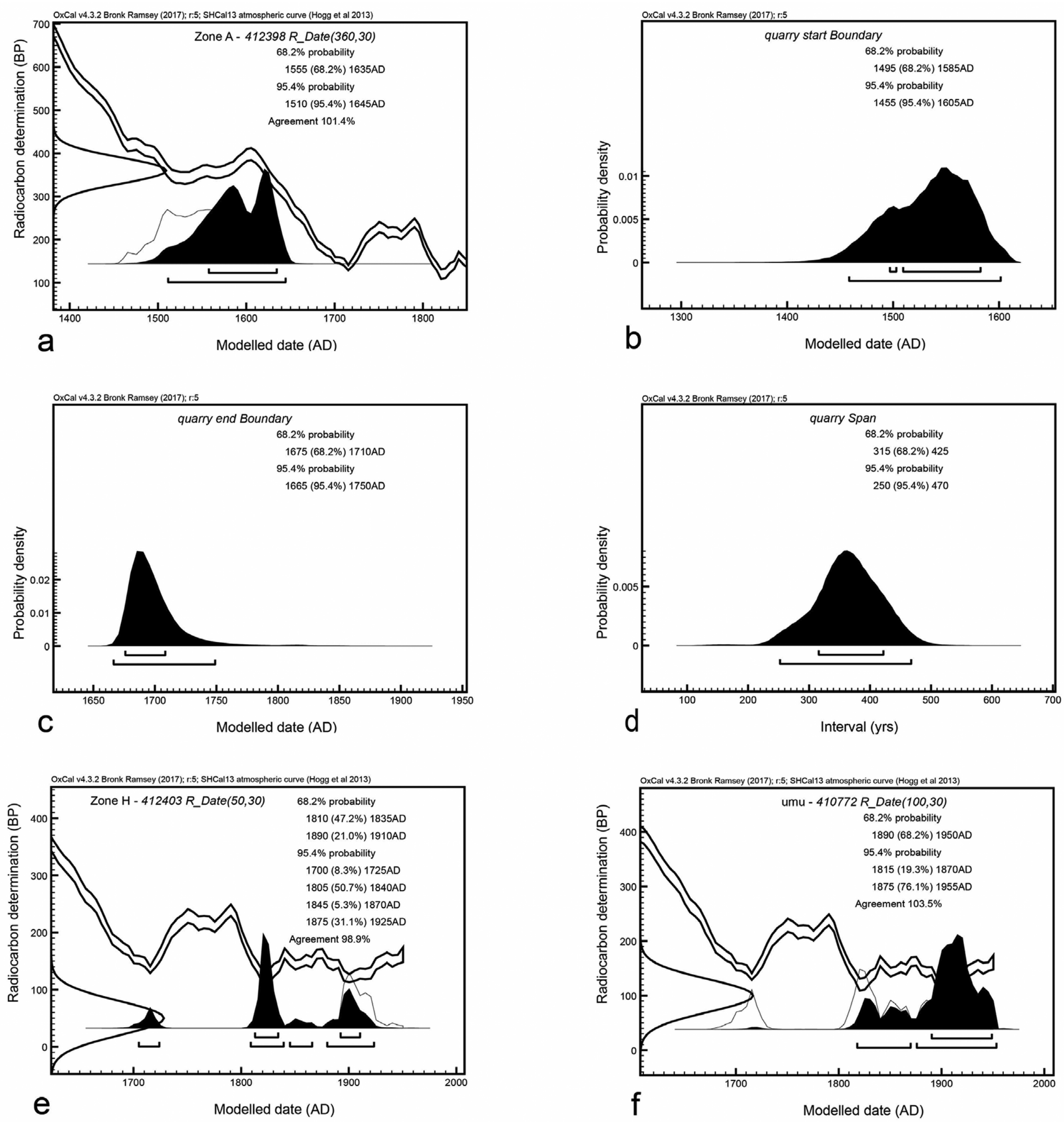


Fig. 14. Modeled dates a) The upper contact of Zone A. This date is the closest to the erection of *moai* RR-0001-156; b) Modeled start of deposition linked to Phase quarry activity 1; c) Modeled end of deposition linked to Phase quarry activity 1; d) Time span the quarrying was active; e) Date from Zone H representing a shift in land-use practices and era of petroglyph carving; f) Fea. 22 *umu* date.

a statistically significant difference in the K in old vs new sweet potato gardens (Walter et al., 2011:79). The Rano Raraku K levels range from 812 to 2030 mg/kg (m = 1360). The New Guinea study interpreted exchangeable K as low (< 50 mg/kg), medium (< 50–120 mg/kg) and high (> 120 mg/kg) demonstrating the phenomenal levels of available K at Rano Raraku. These levels are likely due to the ability of smectitic 2:1 clay to fix K in large quantities and for such clays to provide for high water retention and CEC.

Both macro and micro plant data support a mixed crop system with the presence of banana, sweet potato and taro as well as *Broussonetia papyrifera* (paper mulberry; *mahute*) which is basic to supporting the Polynesian lifestyle and known to have been reserved for Rapa Nui elite at Western contact in 1722 (Métraux, 1940). The entire depth of the *moai* 156 profile reveals certain evidence for vegetation disturbance, with all plant microfossil samples containing charcoal and pollen from open environments, namely grasses, Cichorieae, sedges and hornworts (Figs. 9 and 11). The Cichorieae are highly invasive herbs; hornworts are small inconspicuous plants and some types are associated on Rapa Nui with early, large-scale vegetation and soil disturbance through human use (Horrocks et al., 2012a, 2012b, 2013), as they are in New Zealand and Europe (Wilmshurst et al., 1999; Overland and Hjelle, 2009a).

The presence of *totora* phytoliths throughout the entire excavation profile provides indirect evidence of plant cultivation in Rano Raraku (Fig. 11). Given that *totora* is a wetland plant and that phytoliths are not adapted for dispersal, the presence of *totora* phytoliths in these dryland samples suggests the selective application of water, vegetation or organic sediments from the crater-lake to the soils, probably to augment soil fertility. This is supported by the coincident presence of other biogenic silica, notably diatoms also observed in sediment thin sections.

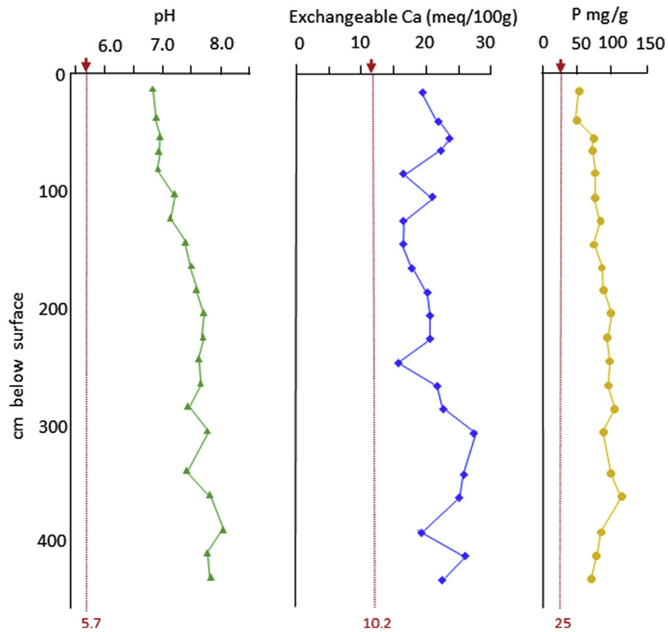


Fig. 15. *Moai* 156 excavation soil data illustrated in vertical distribution for pH, exchangeable Ca + + (meq/100 g), and P (Weak Bray) with the soil chemical thresholds marked in red that are considered necessary for successful intensive dryland agriculture as determined by the Hawai'i Biocomplexity Project (according to results in Ladefoged and Graves, 2000; Chadwick et al., 2003; Ladefoged et al., 2005, 2010).

Although some types of diatoms can live in soils, they are more common in wetland environments. If this is the case, the larger amounts of *totora* phytoliths in the central part of the profile associated with zones G through I may reflect more intensive agricultural activity from the mid 16th through the 17th centuries.

Both macroscopically and microscopically there are no features that suggest any portion of the excavation profile included well-developed paleosols like those visible at lower elevations of the exposed north and west interior edges of the inner region. Those soils show that when the lapilli tuff is stable over time, without augmentation, it becomes a deep chemically weathered plastic clay, with granular pedogenic texture and a characteristic orange-brown color with Fe/Mn redoximorphic features (Mann et al., 2003; Mieth and Bork, 2010; Horrocks et al., 2012a; Dunn et al., 2013, 2015). Whereas sand to gravel-size lapilli tuff fragments on the opposite slope, in the quarry area, produced during hundreds of years of quarry activity, provided a nearly constant stream of "fresh" weathering and nutrient rich matrix in which to grow crops. Similar erosion processes, albeit at a much larger scale, are documented in Hawai'i where colluvium from volcanic shield source material enriches valley soils with the mobilization of fresh rock, effectively rejuvenating the supply of rock-derived nutrients to slope and colluvial soils below (Vitousek et al., 2004; Porder et al., 2007; Palmer et al., 2009: 1445; Kurshima and Kirch, 2011). This phenomenon was likely active on the Rano Raraku exterior slopes as well; however, proximity to the sea and prevailing wind exposure would likely have a greater impact on soil moisture, rendering soils there less fertile than in the inner region.

The highly localized fertile area detected in the Rano Raraku inner region reveals the limitations of modeling agricultural productivity based on large scale proxies (e.g., precipitation and elevation) to explore demographic change on Rapa Nui (e.g. Puleston et al., 2017). The high productivity of Rano Raraku inner region points out a specific case of heterogeneity within the Rapa Nui landscape that such models neglect. While Rano Raraku (at the base) is less than 1% of the island area at 0.6 km^2, it is the single source of the specific type of stone used to produce 1265 megalithic stone sculptural objects or 91.34% of the total sculptural inventory. The Hawai'i Biocomplexity Project identified highly localized conditions that generated soil nutrients especially indicative of P levels > 25 µg/g that they designated as "sweet spots" (Kirch et al., 2004; Vitousek et al., 2004; McCoy and Hartshorn, 2007; Lincoln et al., 2014), and Rapa Nui rock gardens that supplied such soil nutrients as micro sweet spots (Vitousek et al., 2014). These can be found adjacent to weathering basalt outcrops where nutrients enter the soil (Palmer et al., 2009; Ladefoged et al., 2010).

The clear presence of cultivars with potentially high productivity levels in Rano Raraku inner region points to an extraordinary *macro* "sweet spot." Food resource exchange between sociopolitical regions is hinted at in the ethnohistory. First Western contact with the Dutch in 1722 occurred in the western sociopolitical district of Tu'u when a man recognized by expedition leader Jacob Roggeveen as a "King or Head Chief" encouraged the visitors to "go to the other side of the island" where they would find the "principal place of their plantations and fruit-trees, for all the things they brought to us of that kind were fetched from that quarter" (Fig. 1; Corney, 1908:19). That "quarter" is the eastern sociopolitical district of Hotu Iti, which includes Rano Raraku. This appears to suggest that certain areas, perhaps including those deemed population non-viable by the Puleston et al. (2017) model, could have engaged in exchange with other areas with better resources. If we accept that the Rano Raraku inner region was a persistently productive center, then its elevated potential for consistently high yields and apparent elite control over the availability of both the food and such desired products as paper mulberry, there is a high potential for far-reaching social impact.

We venture the novel suggestion that based on these data, and on the ritualization of Rano Raraku and its stone as megalithic resources, Rano Raraku soil/sediment itself was a valuable and protected commodity. Soil could have been transported from Rano Raraku to enrich those areas needing increased productivity. The Rapa Nui archaeological record is replete with evidence for the quarrying, extraction, transport and exchange of ritualized natural materials used for ceremonial purposes. These include red stone from Puna Pau quarry to embellish ceremonial sites (*ahu*) but also to carve *moai* and *moai* eyes and construct tombs and crematoria (Mulloy, 1961; Van Tilburg, 1986; Vargas et al., 2006); *totora* reeds for burial mats in *ahu* tombs (Smith, 1961); pigments in a range of colors from circumscribed sources for body art; coral from named offshore fishing grounds for *moai* eyes and crematoria (Ayres, 1973, 1979) and fine-grain basalt for the massive stones (*pa'eŋa*) that made up elite house foundations (McCoy, 2014).

5.2. Chronology and activity in Rano Raraku beginning in the late 15th century

The modeled dates in their stratigraphic context in relation to *moai* 156 and the density and visibility (and therefore assumed use) of its secondary petroglyphs allow us to visualize human use of Quarry 2. The model indicates that major megalithic quarrying to create *moai* of "classic" size and proportions in and around Quarry 2 continued into the late-15th and 16th centuries, with use of Quarry 2 likely ending before the late 18th century. Early in this period *moai* 156 was set upright in place while other activities continued around it, some of which were likely ceremonial as reflected in the presence of red pigments. Stratigraphy above Zone A shows periodic pulses of sediment moving downslope after *moai* 156 was erected. The relative abundance of macroartifacts, the presence of incipient surfaces in this part of the excavation and the availability of sediment suggests that quarrying and/or significant earth disturbance continued, although likely at levels below those for the most intensive period of megalithic production, which by all available evidence was during the 14th century (Mulloy, 1961; Ayres, 1973; McCoy, 1976; Mulloy and Figuroa, 1978; Van Tilburg, 1994; Green, 1998; Wozniak, 2003; Vargas et al., 2006; Mulrooney, 2013).

Zone H, ca. 220 cmbs, defines the area of abundant pecking and incising of petroglyphs on the back of *moai* 156. These include a few that are modern but mostly composite symbols based upon the crescent and fishhook motifs and the reclining composite crescent which includes the "birdman" (*taŋata manu*) motif of 'Oroŋo ceremonies. These petroglyphs and similar motifs on adjacent *moai* 157, along with cessation of the initial phase of sediment deposition noted above, allow us to suggest that this inscribed surface was created just prior to European contact (Routledge, 1919; Lavachery, 1939; Métraux, 1940; Englert, 1978; Lee, 1992).

This radiocarbon model is the first solely archaeological Bayesian model published for Rapa Nui. Our data provide an opportunity to define questions and refine the chronology for Rano Raraku inner region using a deep stratigraphic context where site formation processes are carefully considered. Rull (2016) has developed a robust radiocarbon database from lake sediments and peats from the island, but as the author notes these contexts come with their own set of challenges such as chronostratigraphic gaps and age inversions that target landscape change but are, in the end, only proxies of human activity. While it is important to integrate archaeological evidence with climatic and ecological events it is also necessary to have robust archaeological contexts for proposed human activities. The model reported here provides such context and has potential for expansion through incorporation of additional dates.

6. Conclusions

This study takes a significant step toward understanding environmental constraints in concert with human landscape modifications within the agrarian economy and hierarchical social system of Rapa Nui's marginal environment. We provide empirical chronological data for the trajectory of *moai* production and abundant botanical evidence of cultivars buried in the south slope of Rano Raraku inner region including especially sweet potato, banana and paper mulberry, further amplified by additional evidence of taro and possibly bottle gourd from lake core data. These data reveal a mixed-crop production system located for an extended time among the quarries and standing *moai.* The carved head (RR-0001-230) associated with *moai* 156, taken in context with the iconography of applied petroglyphs and the identification of recovered materials such as red pigments and coral, both of which have well-documented ritual uses, suggests a ceremonial role for the *moai* even as quarrying declined and eventually ceased. There is still much to learn about the Rapa Nui ecosystem development, land management and adaptable ceremonial concerns. However, the richly endowed agricultural area of Rano Raraku inner region detailed here and specifically the soils contained within it offer new, dynamic and more nuanced insights into the interactive nature of the prehistoric Rapa Nui *moai* production system and its related economy.

7. Notes

1. Radiocarbon date 410744 has been modeled as an outlier but we do not use an OUTLIER MODEL. We treat this as an outlier within our model since it is an unusually late date, despite being recovered over four m below surface. Our first modeling attempt with this sample did not importantly affect the model's overall output or fit with the data, but sample 410744 did have an individual agreement index below 60. It is possible that this sample's result is a statistical outlier, as one in 20 radiocarbon ages is expected to lie beyond the reported two-sigma error range (Bronk Ramsey, 2009: 5; Hamilton and Krus, 2018: 199). In Fig. 12 sample 410774's calibrated date is displayed, but because it is modeled as an outlier it has no effect on the model's output.

Acknowledgements

We gratefully acknowledge EISP co-director and excavator Cristián Arévalo Pakarati, EISP database manager Alice Hom and the following excavation funders and supporters: Archaeological Institute of America Site Preservation Committee Grant 2; Easter Island Statue Preservation Foundation (45-4057949) www.eisp.org; Steinmetz Family Foundation / Steinmetz Family Trust (642-650); Cotsen Institute of Archaeology, UCLA Friends of Archaeology Director's Council; Gillespie Family; A'lani Kailani Blue Lotus White Star Foundation (35-6894268); Dinging for Change Foundation 2017-4613, SFC Grant 15; 2017:4. The following institutions provided permissions and/or field support: Consejo de Monumentos Nacionales; Comisión Asesora de Consejo de Monumentos Nationcales Rapa Nui; Corporacion Nacional Forestal, Rapa Nui; Centro Nacional de Conservación y Restauracion; Gobernación de Isla de Pascua; Municipalidad Rapa Nui; Museo Antropologico Padre Sebastian Englert; Museo Nacional de Historia Natural. The following individuals provided specialized excavation documentation, preliminary reports, illustration preparation or significant comments on the data: Matthew Bates, Monica Bahamondez Prieto, Greg Downing, Sonia Haoa Cardinali, Christian Fischer, Alice Hom, Jennifer Huebert, Debra Isaac, Audrey Kopp, Jeffrey Morris, Susan Morris, Gail Murakami, Edward Schoch, Scott Torreano, Amanda Tsai, Shelley Wachsmann, and Deidre Whitmore. We thank the two anonymous reviewers for taking the time to help improve the quality of this manuscript.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jas.2019.104994.

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