Geoarchaeological Investigation of Agricultural Terraces in Pualaulau, Hālawa Valley, Moloka‘i, Hawai‘i

Kylie Aiea Tuitavuki

<u>Committee Members</u>

Committee Chair: Patrick V. Kirch; pvkirch@hawaii.edu
Committee Member: Noa Lincoln; nlincoln@hawaii.edu
Committee Member: Seth Quintus; squintus@hawaii.edu

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Introduction

Islands have served as model systems for understanding processes in evolutionary biology and ecology since Darwin made his first observations on Galapagos finches. Fast forward more than 150 yeras hundreds of years and this evolutionary framework, specifically within the context of island ecosystems, has been applied to a multitude of other disciplines, including studies in geography, resource management, and more recently the field of historical ecology. Islands in the Pacific have been used as laboratories for investigating the evolution of cultural practices, environmental processes, and the dynamic relationship between humans and the ecosystems they occupy. The geographic, geologic, and biologic constraints that naturally occur on islands allow for specific variables to be examined and controlled for. The location and known range of human occupation in the Pacific makes Polynesian islands ideal for understanding human-induced landscape modifications, specifically those that involve large-scale agricultural changes driven by socio-political and demographic needs. By studying changes in landscape modification and resource management practices visible within the archaeological record, anthropologists and historical ecologists can offer insight into how these practices were utilized in the past. Understanding how past agricultural and landscape management practices evolved, were managed, and how sustainable (environmentally and production wise) they were in the past, could allow for further application to modern day policy and resource management techniques.

The current climate and demographic crisis being experienced by the global population calls for immediate change in the way that resource utilization and landscape modifications are currently being done. One of the largest and most ancestral forms of landscape modifications is agricultural, whether it be small scale gardening for subsistence living or large-scale industrialized methods being used to meet current demographic needs. Agricultural systems on islands provide good case studies for studying landscape modification, resource allocation, and the potential sustainability of these systems. The Hawaiian Islands offer a unique environment for analyzing how geomorphological constraints shaped landscape modifications, creating environmental legacies that were further developed under specific socio-political systems. Studying the life history of agricultural and land management systems, in combination with the incorporation of traditional ecological knowledge, has the potential for revitalization and application in modern agricultural systems, offering potential alternatives that could be essential in changing the environmental fate of our planet.

This study investigates the archaeological remains of a terraced agricultural system in the 'ili of Pualaulau in Hālawa Valley, Molokai, posing the question of whether the terraces were formerly irrigated. The location of the terraced agricultural system is slightly northwest of what today is an intermittent stream. Past climate data suggests that seasonal rainfall may have allowed for potential irrigation of the terraces during the rainy season. Varying levels of seasonal rainfall suggest that this terrace system could have been seasonally irrigated, diversifying its uses for potential year-round cultivation.

Geoarchaeological methods are used to determine 1) whether terraces within the designated dryland agricultural system were potentially seasonally irrigated, and 2) how frequently seasonal irrigation was used in this terrace system. Particle size analysis (PSA) and an assessment of sediment particle angularity are used to determine the origin and mode of deposition of sediment particles within the terraces. Samples from a natural colluvial slope, from known dryland terrace systems, and from the adjacent streambed serve as controls for samples collected from the agricultural terraces. My working hypothesis is that sediment samples that were transported fluvially should express a particle size distribution and grade of angularity like the inlet or stream bed control samples. Sediment samples collected from test units that were seasonally irrigated should express physical characteristics that likewise more closely resemble the inlet or stream bed control samples, while samples from non-irrigated contexts should more closely resemble the colluvial slope control samples.

Background Research

The Hawaiian Islands are the northern most islands in the Polynesian Triangle and the most remote archipelago on the planet (Kirch 2007). This island chain is a classic example of a linear, age-progressive island chain, with island emergence resulting from the extrusion of basaltic lava from the seamount floor over a fixed "hot spot". Tectonic plate movement in a general northwest direct creates an island chain, with age progression that decreases from west to east, with the oldest island in the main part of the island chain being Niʻihau at 5.55 mya in the far west, and the youngest being Hawaiʻi island at 0.6 mya (Kirch 2007). This age gradient presents a series of islands belonging within the same archipelago that have different geological histories, and therefore different soils at various stages of development, freshwater resources, and marine resources and reef formations, all of which influenced the cultural and sociopolitical developments on these various islands (Kirch 2017). Younger islands exhibit far less erosion with minimal streams and valley development, have soils that are typically rocky and underdeveloped, with high concentrations of rock-derived nutrients (mainly phosphorous) which has the potential to influence land use, specifically for agricultural production (Vitousek et al 2004, Lincoln 2019). Older islands, on the other hand, have had more time to develop and undergo natural landscape modifications, resulting in deeply eroded valleys with permanent or semi-permanent streams for colluvial/alluvial cultivation, and diverse shorelines with high levels of biodiversity. However, the deeply developed soils of these older islands are typically lacking high levels of phosphorous and other rock-derived nutrients needed for agricultural practices, but is not necessarily true in valley bottoms which are frequently rejuvenated by eroding and falling cliff face (Lincoln 2019). These biological and geomorphological differences significantly influenced the placement and development of pre-contact agricultural systems, and in turn, the sociopolitical structures supported by these systems.

Microclimates on individual islands also influenced the type of agricultural systems implemented on specific islands. Northeast trade winds, combined with great variations in geologic topography create zones with some of the most dramatic rainfall gradients on Earth, resulting in two drastically different environments on windward and leeward sides of individual islands (Vitousek 2002). The variation in annual levels of mean precipitation can be as great as 4000 millimeters on windward slopes and 500 millimeters on leeward slopes, even though distances between these two sides can be as little as 20 kilometers from one another (Kirch 2007). The drastic differences in available rainfall determined which agricultural practices were implemented in different areas of each island, creating a sociopolitical system that was dependent on continual interaction and trade between groups cultivating different crops. These biological and geomorphological features were already present and acting on these island ecosystems before Polynesian voyagers first reached the Hawaiian Islands around 1000 AD (Kirch 2017). The framework upon which the entirety of the Hawaiian agricultural and sociopolitical systems stems from the pre-existing biological and geological limitations already acting on these islands.

One of the most obvious forms of landscape modifications present on the Hawaiian Islands is the Polynesian "transported landscape", a concept originally developed by Edgar Anderson (1952), and later applied by Kirch (1984) to Polynesia. Transported landscape refers not only toa specific set of flora and fauna that were brought with voyagers as they traveled and settled across the Pacific (the so-called "canoe plants"), but also indigenous concepts of land use and agricultural practice. High presence of charcoal, a decline in endemic flora and fauna, the first appearance of introduced species serve as proxies for first signs of human arrival. Initial populations were low in numbers, with noticeable landscape transformations first taking place in specific, concentrated areas. Population size and density, specifically in areas already restricted in size, greatly modified the natural landscape. Population distribution was restricted by the previously mentioned biogeographical factors, with most inhabitants concentrated in lowland areas, primarily in windward or transitional regions with freshwater resources, nutrient rich soils, conducive of highly productive agricultural zones (Kirch 2007). Population reconstructions suggest that "permanently inhabited lands…made up no more than 25 percent of all land area, suggesting an 'average' population density of roughly 95 person per square kilometer" (Dye 1994). Increases in the presence of charcoal in the archaeological record serve as proxies for human growth, if large scale, high intensity burning was used as a mechanism of forest clearing for settlement and agricultural construction. Dye and Komori, as cited in Kirch 2007 created a curve for population growth rates from collected radiocarbon samples, concluding that, 1) Hawaiian population dramatically increased during the first major period of expansion, growing exponentially until reaching its beak around 1450 CE and 2) population growth abruptly stopped, reaching what appears to be a carrying capacity, fluctuating around this maximum until European contact. While this work offers a general population reconstruction, it fails to acknowledge preference for specific areas that are shaped by the potential for agricultural productivity.

Production and Population Growth

Earle (1987, 1997) and Kirch (2007) note that the Hawaiian political economy was one of 'staple finance' where wealth and power was determined by staple and tangible possessions. The control of food surplus and agricultural production could be used to gain power, which was a key component for the sociopolitical transformations Hawaiʻi experienced just before contact. Kirch (2007) and Allen (1991) state that Hawaiian political systems probably started off as chiefdoms, like most other Polynesian societies. However, archaeological and paleoenvironmental data show a strong transition to an 'archaic state', with land rights based on kin group membership and residency being replaced by a small hierarchy of elites, with a king at the top (Kirch 2007). Land was divided into *ahupuaʻa*, territorial units running from the mountain to the coast, which included a range of planting zones for optimizing production. The implementation of these systems and management by a centralized power quickly led to intensification of these agricultural systems, with *ka makaʻāinana* being obligated and having *kuleana* to a specific parcel or area of land. This is most obvious in the dryland systems, particularly the Kohala field system, where the extensive network of walled divisions not only showed further division of land but can provide a chronology of intensification by analyzing when specific walls were constructed (Dye 2014). Distribution of goods and resources within these systems was highly dependent on elites, with all surpluses of yields being offered as tributes. So, while these systems may appear to be highly productive based on paleoenvironmental factors and climate data, unrealistic labor inputs that are mainly based on the implementation of these very extractive and intensive sociopolitical structures, have greatly skewed ideas about the potential reimplementation of these systems in a modern context.

There are two main theories regarding function and production that must be applied to the intensification of agricultural systems in Hawaiʻi, especially in relation to changing demographics. The Malthus production-finction theory states that populations will grow in a natural manner until held in check by natural limitations in either the food supply or other natural resources that are vital to the success of a population (Soby 2017). In essence, Malthus believd that popualtions increased in an exponential manner, slowly at first and then rapidly increasing over a short period of time once natural resources and food sources were established. However, agircultural production tends to grow in a linear or arithmetic manner, at a constant rate that will never truly meeet the demans of exponential population growth (Soby 2017). The concept of a carrying capacity (K) was then applied to Malthus' theory of production, demonstrating that there is a certain carrying capacity that can be supported by any form of agricultural production if there is enough surplus available. This concept was further elaborated on by Boserup, who recognized that human innovation could potentially change the dynamics of agricultural production as it relates to carrying capacities (Soby 2017).

Boserup agreed that carrying capacity was a limitation to production growth but suggested that this carrying capacity was variable rather than fixed. She suggested that technological adaptations would allow for an increase in carrying capacity, with new innovations in agricultural production aiding in population survival even when under specific environmental pressures. These two theories combined created the MaB (Malthus-Boserup) Ratchet concept, which demonstrated that as populations reaches a certain carrying capacity, they experience extreme pressures which are then alleviated by some sort of cultural innovation, creating a new carrying capacity and the survival of that population (Soby 2017). When comparing the MaB Ratchet concept to either Malthus' or Boserup's original ideas, it appears to look more like a stepwise function, where populations reach a certain carrying capacity under specific conditions, but an innovation allows for an increase or 'jump' in carrying capacity, allowing for more growth. Understanding the MaB Ratchet concept as it relates to agricultural production in the Pacific is essential in understanding how dryland systems were intensified to accommodate a growing population size and changing social dynamics.

Pre-Contact Agricultural Systems

Implementation of agricultural practices appear as “mosaic agroecosystems” over the Hawaiian landscape, being a mix of dryland and wetland agricultural systems tailored to specific island zones (Kirch 2017). Wetland agriculture consists of mainly irrigated monocropping of taro with dams and canals diverging water from permanent streams, resulting in landscapes that are permanently modified because of these structures (McCoy and Graves 2010). These systems are highly productive, yielding large crops without requiring lengthy fallow periods between crop cycles (Kirch 2007). However, given their need for large amounts of easily accessible water, they are mainly present on the windward sides of geologically older islands including Kaua‘i, Oahu, Moloka’i, and western Maui that have more developed freshwater sources. These areas, mainly concentrated in colluvial/ alluvial zones found within valley bottoms, create landscape legacies that can dictate potential for future reuse (Kurashima and Kirch 2011). The developmental history of these agricultural zones is of great interest to archaeologists and historical ecologists, being some of the strongest supporting data sets for the movement towards revitalizing and potentially reimplementing these systems in Hawai‘i if they are as sustainable and productive as scientists assume them to be. These systems developed from small plots originally designated for long-fallow shifting cultivation yet became progressively more formalized with the implementation of stone walls to mark ownership, eventually leaving permanent structures preventing any future use of the land (McCoy and Graves 2010). Although these agricultural systems were vastly different from one another, they both left lasting impressions on the landscape and changing the potential land use of these areas.

Recent studies have also highlighted the importance of colluvial slope agricultural systems located in valley basins, which have higher potential for long-term use due to fluvial runoff from surrounding cliff face (Kurashima et al 2019). Kurashima et al. (2019) developed a spatial distribution model for indigenous agroecosystems across the Hawaiian archipelago, suggesting that these traditional systems had the ability to support a population just under 800,000 people. Their work modeled potential distributions of wetland (lo‘i), dryland, and colluvial agricultural systems, totaling 100,789 hectares of land across all islands that could support some form of indigenous agriculture (Kurashima et al. 2019). Of that land, 12.7% could support *lo‘i* agriculture, 52.7% could support dryland agriculture, and 34.6% could support colluvial-slope agriculture. These predictions were made by combining current environmental and climatic conditions with paleoenvironmental data from the period immediately before Captain James Cook’s arrival to Hawai‘i in 1777-78.

Hālawa Valley, Moloka‘i

Hālawa Valley on eastern Moloka’i was selected as our research site based on previous and current archaeological research that has focused on the extensive archaeological remains of both irrigated and dryland terraced agricultural systems throughout the valley. Hālawa Valley is the easternmost of four amphitheater-headed valleys on the island of Moloka’i, with an average yearly rainfall well over 3000mm, allowing for extensive irrigated cultivation during the pre-contact and historic periods (Kirch and Kelly 1975). Hālawa Valley is approximately 2 square kilometers in size, nearly 3km deep and 1km wide at the mouth of the valley and includes the coastal dune areas along the beach front. There are three main geological zones within Hālawa Valley, including bare rock outcrop on the cliff face, lower shelves which provide good erosive material for nutrient replenishment, and the alluvial terraces which allow for both dryland terraced agriculture in the upper systems and more intensive pond field irrigated systems in the lower flats (Kirch and Kelly 1975). In the early to mid 1800s, Hālawa was described as having intensive taro irrigation complexes that were able to support a population of at least 500 individuals. Upon his visit in 1853, Marston Bates noted that taro was cultivated in Hālawa Valley on a massive scale, and that the sale of this crop to the whaling fleet at Lahaina, Maui, made Hālawa "the richest spot of the island" (Bates 1845). Ethnographic and previous archaeological studies make Hālawa Valley an ideal study site for further investigation of both irrigated and dryland terraced agricultural systems.

Previous work by Kirch and Kelley (1975) and Kirch (1990) document Hālawa Valley's settlement patterns, agricultural structures, and residential complexes. Work conducted by Krich, Riley, and Hendren in Hālawa Valley from 1969 – 1970 mapped and documented the remains of an extensive irrigated lo‘i agricultural system, which totaled 693 pond field terraces within 9 separate irrigation complexes (Kirch and Kelly 1975). These complexes range across the full suite of Hawaiian irrigation structures, including small, tributary-stream irrigated terraces to large, flood-plain systems supported by a dual ‘auwai (canal) system (Handy 1940; Kirch 1977). This study aims to investigate the upper dryland agricultural structures to compliment previous archaeological work in the lower irrigated areas, including structures in the ‘ilis of Kapana and Pualaulau, which were both previously mapped by Stokes (1909) and later by Kirch and Kelly (1975).

Agricultural and soil studies by Vitousek et al (2010) also provide a foundation for further geoarchaeological investigation of agricultural systems throughout Hālawa Valley, including geospatial modeling and agricultural distributions and the long-term sustainability of these systems. Preliminary analysis of soil nutrients from colluvial (non-irrigated) and alluvial (irrigated) soils throughout Hālawa Valley demonstrate that colluvial soils have a much higher nutrient content compared to alluvial soils. This is most likely due to erosion from upper cliffs, allowing replenishment of vital soil nutrients and minimal amounts of leaching due to lack of consistent water flow.

This study was designed as a component of a larger collaborative project in Hālawa Valley, "Soil, Nutrient Cycles, and the Development of Sustainable Hawaiian Valley Agro-Ecosystems from 1200 – 100 yr B.P," which is a two-year collaborative project co-directed by P. V. Kirch and J. Swift and funded by the National Science Foundation with the main goal of investigating the long-term agricultural sustainability of Hawaiian indigenous cropping systems.

The Study Site

The ‘ili (traditional land section) of Pualaulau is located on the southern extent of Hālawa Valley, situated between the ‘ili of Wai'oli on the makai side and the ‘ili of Kapana on the mauka side. A small side-stream (Pualaulau Stream) runs through the ‘ili and meets the main Hālawa Stream further downslope; today this stream only runs intermittently after heavy rains. The area we investigated during this study includes the valley slopes west of Pualaulau stream until the steep ridge separating Pualaulau and Kapana. A USGS map of Hālawa Valley, including specific locations of both Pualaulau and Kapana can be seen in Figure 1. This area primarily consists of colluvial slopes, with many intact archaeological remains of dryland terraced systems, which provides us with the opportunity to more closely investigate these terraced, colluvial slop systems. This area is steep, with large boulders and other rock fall that have eroded from higher cliff faces.

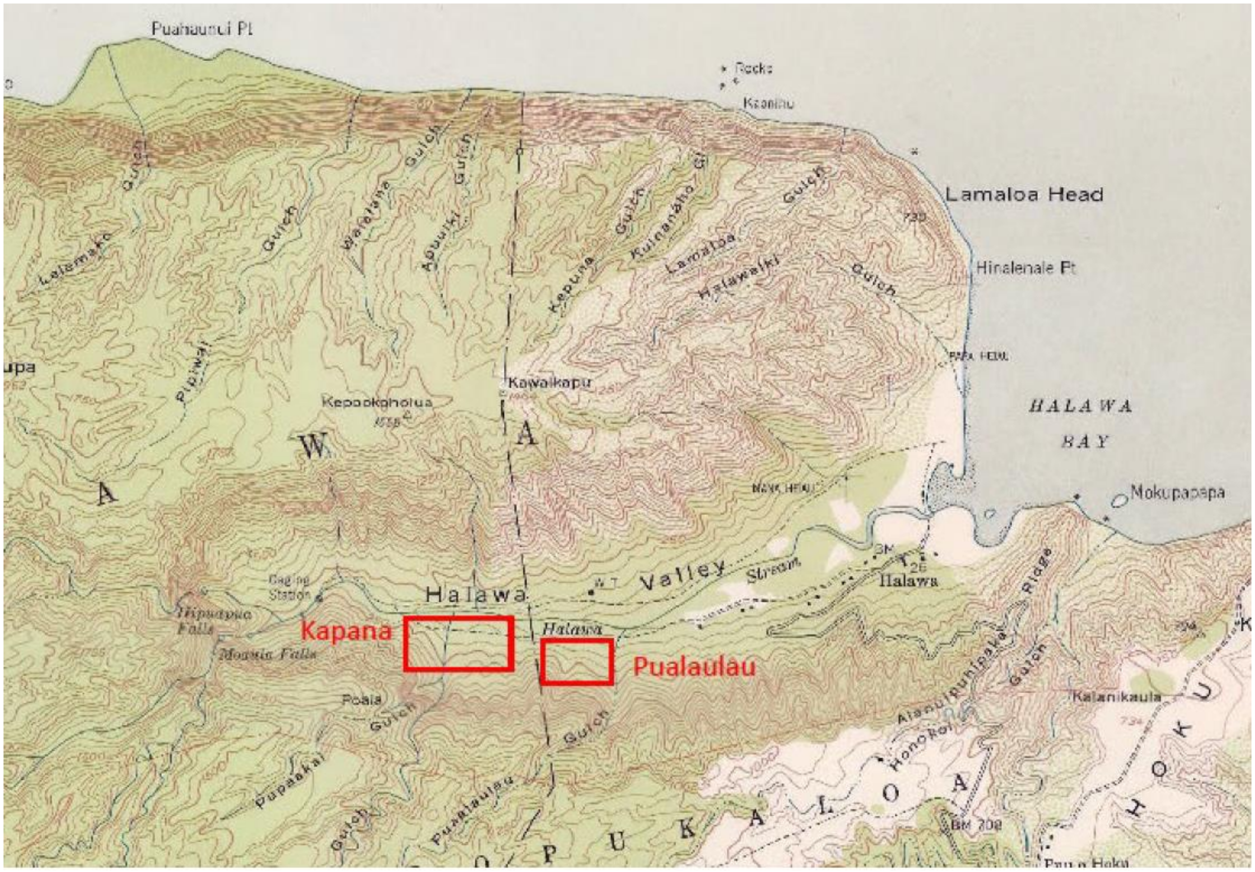

Figure 1. Map of Hālawa Valley, Moloka'i taken from USGS Hālawa quadrangle, with locations of Pualaulau and Kapana outlined in red.

A larger dryland, terraced agricultural system was initially mapped in this area, including excavations from several potential habitation sites and potential heiau (temple site), that should be included in the analysis of the overall complex in Pualaulau. Two maps were created by P. V. Kirch for this area, a larger map that covers the extent of the study area in Pualaulau, including all test units and other features recorded, and a smaller more detailed map that includes the upper portion of a barrage, or stepped, terrace system that is the location of interest for this study. This upper barrage terrace system was selected for investigation due to its location just northeast of Pualaulau stream and for the intact terrace wall structures. The uppermost terrace in this system is slightly higher in elevation than the adjacent stream bed but could have been at the same elevation in the past. This would potentially have allowed for water to be diverted from Pualaulau Stream into lower agricultural terraces during times of heavy rainfall and stream flow. The agricultural system continues down the slope of the valley, with terraces running along the stream until the bottom of the complex. There are several smaller inlets along the length of the stream that suggest water could have been diverted for potential irrigation in the lower terraces of this system. A map of Pualaulau can be found in Figure 3 and a more detailed map of the upper Pualaulau barrage terrace system can be found in Figure 4.

An updated map of Kapana ‘ili, previously surveyed by Podmore (1915), was drafted to document the excavation of the irrigated terrace systems associated with this area. Previous work by Podmore (1915) details irrigated agricultural systems in areas between alluvial flats and the colluvial slopes, which was used as reference for the barrage terrace of interest in this study. A more recent map of the smaller side-stream irrigation system in Kapana, including location of test unit excavations, can be found in Figure 11.

Research Objectives

Based on our understanding of the landscape within Pualaulau, we hypothesize that the barrage terraces identified in the 2020 Kirch and Swift archaeological survey could be seasonally. The main objective of this project is to determine whether sediment samples collected from test units within the barrage terrace system located in the ‘ili of Pualaulau were express characteristics that support the idea that this terrace systems was seasonally irrigated. A series of geoarchaeological methods will be used to investigate this hypothesis, in particular particle size analysis (geoarchaeology) and the assessment of angularity of particles.

Field Methods

Site Survey and Mapping

Site selection was determined based on previous studies of Hālawa Valley, including recent work conducted by Kirch and Ruggles and foundational works by Stokes (1909), Kirch and Kelly (1975), and Vitousek et al (2010). Mapping and excavation took place in two ‘ili on the southern portion of Hālawa Valley: Kapana and Pualaualua. While Kapana ‘ili had been mapped during previous field work (Kirch and Kelly 1975), extensive and detailed mapping of Pualaulau had not been done in previous studies, providing us with the opportunity to produce fine-scale maps of this area. A Gurley telescopic alidade and plane table was used by P. V. Kirch to produce detailed maps of Pualaulau ‘ili at a 1:200 scale. A more detailed map of a side stream irrigation system located in Kapana ‘ili was also drawn using the plane table mapping method at a scale of 1:100. GPS locations of 22 mapping stations recorded via a Trimble Juno system (Kirch and Swift 2021). Hand-drawn plane table maps were digitized using Adobe Illustrator and combined with GPS data to georeference all plane table maps with a pre-existing GIS database for Hālawa Valley.

All areas used for survey and excavation work were on land belonging to Pu’u o Hoku Ranch.

Test Unit Excavation

A total of 22 small-scale test unit excavations were placed in selected features throughout Pualaulau and Kapana, including agricultural terraces and house sites. All test units were placed abutting *in situ* stones of architectural features with the goal of obtaining charcoal for radiocarbon dating. Test unit dimensions varied in size depending on surrounding environmental constraints, but were a minimum of 50 cm (l) x 50 cm (w) in size. Due to the agricultural function of terraces that test units were placed in, excavation was conducted by natural stratigraphic layers, subdivided into arbitrary 10 cm levels, using the pick-and-shovel method. Units not placed in agricultural terraces were excavated with hand tools (trowel and small hand picks) in natural stratigraphic layers, subdivided into arbitrary 10 cm levels. Upon completion of excavation, test units were backfilled, and the ground was restored to original condition.

Given the function and natural erosion occurring in these areas, we did not anticipate high amounts of preserved cultural material. More precise excavation methods would be employed if large amounts of charcoal or cultural material were encountered during initial excavation practices, including the implementation of smaller arbitrary levels (5 cm) excavated with hand trowels, hand picks, and small brushes.

All excavated sediment was sieved through a 1/8" screen unless otherwise noted. Finds were bagged according to context and artifact type. An inventory of materials was recorded in an Excel spreadsheet at the end of each week.

Sediment Sampling

Sediment samples were collected from 10 of the total 22 test units. These 10 test units were chosen for the placement in agricultural terraces, most of which were either dryland or seasonally irrigated via diverted irrigation channels during periods of high rainfall. Samples were collected from test units in both Pualaulau and Kapana. Sediment samples collected from Pualaulau ʻili were taken from test units located in the uppermost side-stream irrigation system. Test units in this area were initially thought to have been rain-fed, but after surveying the surrounding area, we hypothesized that they might have been potentially irrigated. Sediment samples were taken from 5 different test units located throughout this upper terrace system. Sediment samples were collected from natural stratigraphic layers throughout each unit. Sediment samples taken from test units in a known irrigated terrace system in Kapana ʻili served as controls for a known irrigated terrace system. Three test units located in the main irrigated system were chosen for geoarchaeological sampling, with samples collected from each stratigraphic layer. Additional sediment samples were collected for control comparisons, including samples from non-irrigated agricultural terraces, a stream bed, and two stream inlets that are seasonally irrigated.

A total of 30 samples were collected and stored in Whirlpak bags, labeled as "Granulometry Samples", and taken back to the Oceanic Archaeology Laboratory at the University of Hawaii at Mānoa for lab analysis (described below).

Laboratory Methods

Particle Size Analysis (Granulometry)

Particle size analysis (granulometry) was used to determine distribution of different sediment particle sizes in the samples collected from the terraces and the control contexts. The size and distribution of sediment particles can be used to infer the means of deposition within an archaeological context. High energy fluvial (water-transported) environments often have sediment distributions that are well sorted, while low energy environments, such as colluvial systems, have course and poorly sorted sediment distributions (Hassan 1978). When combined with other characteristics, such as angularity, particle size analysis can be a good method for inferring depositional environment. Variation in sediment particle size distribution between units throughout Hālawa Valley provide us with insight into how landscapes were used in different microenvironments, while changes in particle size distribution within each unit presents us with an image of past landscape modification.

A standard protocol for conducting particle size analysis was adapted from Folk (1964). Prior to starting particle size analysis, 25 g of each sediment sample were removed from bulk sediment samples to sample for pH. For particle size analysis, each sediment sample was weighed and placed into a 500 ml beaker. Samples in beakers were then dried in a Model 30 GC Lab Oven at 110° for a total of 16 hours, with the intent of sterilizing samples while avoiding burning off any important inclusions. Samples were then removed from the oven, allowed to cool, and then reweighed to determine final weight of sediment sample. Samples were then weighed out to 100 g; 50 g was used if 100 g were not available, and the entirety of the sample was used if less than 50 g were available. A series of 6 nested geological sieves were stacked in ascending order, ranging from > 4mm to < 0.05 mm in size. Pre-weighed samples were then poured into the stacked sieves and placed in the Humboldt Motorized Sieve Shaker for a total of 10 minutes.

Nested sieves were removed at the end of the 10 minutes and the contents of each sieve size were individually weighed and recorded. The process was repeated for all 30 samples.

Determination of Angularity

The shape, size, and orientation of sediment particles can also be used to determine means of deposition within an archaeological context. Sediment that is rounded or subrounded are often deposited by fluvial means (Hassan 1978). Environments that are high energy, such as rivers, streams, and even irrigation canals, often produce more rounded sediment particles due to wear and abrasion while in motion (Hassan 1978). Sediment particles that are more angular are often transported and deposited in more sudden ways such as landslides, bioturbation, or other means that do not allow for long term erosion. The angularity of sediment particles within these agricultural terraces can be used to infer their means of deposition, with more rounded sediment particles suggesting possible fluvial deposition and more angular particles suggesting more sudden or minimal movement.

In addition to particle size analysis, surface texture or particle angularity was also used on selected phi sediment sizes. The level of angularity of individual sediment particles can help distinguish origin, transport agent, and depositional history of sediments (Folk 1964). Samples of phi class -2 (> 4mm) and -1 (2mm – 4 mm) were used to determine surface texture and angularity. 100 sediment grains from each sieved sediment sample were selected and classified at random according to the Powers ordinal classes (1953). Powers’ ordinal classes of angularity fall on a scale of 1 (very angular) to 6 (very rounded). A diagram of Powers’ (1953) ordinal classifications is included below (Fig 2).

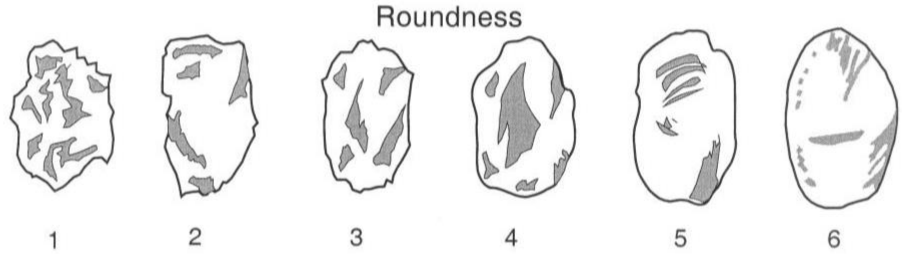

Figure 2. Diagram of Power's ordinal classification of sediment angularity which was used to classify degrees of angularity for sediment samples collected in this study (Powers' 1953).

Results

Test Unit Excavations

The Pualaulau Side-Stream Terrace System

The Pualaulau Side-Stream Terrace System, designated as 50-MO-A1-1016 by Kirch and Swift, is located on the eastern portion of the Pualaulau ʻili during the 2020 field season. Most of the areas surveyed and excavated during the 2020 field season were most likely rainfed or seasonally irrigated, given their location within the ʻili and construction within the valley (Kirch and Swift 2020). A map of the complete area survey in 2020 and constructed by P.V. Kirch can be seen in Figure 3. Based on its location and construction, we hypothesize that this terrace system was irrigated by water diverted from Pualaulau Stream, which could have had higher water levels and flow rates compared to today. A plane table map of the 50-MO-A1-1016 (Fig. 4) demonstrates the potential water flow from the diverted system, through a remnant stream bed on the eastern portion of the system, and down through the subsequent terraces. The side stream irrigation appears to terminate at a large, well-constructed terrace built into a natural rock surface, roughly 3-4 boulder courses high (Kirch and Swift 2020). A total of 5 test units were placed and excavated throughout this system, beginning with TU-10 which is closest in proximity to Pualaulau Stream, three test units throughout the main body of the terrace system (TU-11 – TU-13), and a final test unit (TU-14) in the terminating terrace at the bottom of the system.

Test Unit 10

TU-10 is in the uppermost portion of the ʻili of Pualaulau and makes up one of the uppermost terraces in this terraced agricultural system situated adjacent to Pualaulau Stream. This terrace was selected as the first of several terraces excavated in this potentially irrigated side-stream system because of its flat nature and proximity to Pualaulau Stream. This terrace is level with the streambed of Pualaulau Stream, suggesting that it could have been used as an inlet to divert water into the downslope terrace system (Kirch and Swift 2021). Sediment from this area was extremely gravely, which might suggest that the area was used for water transport as opposed to agricultural production.

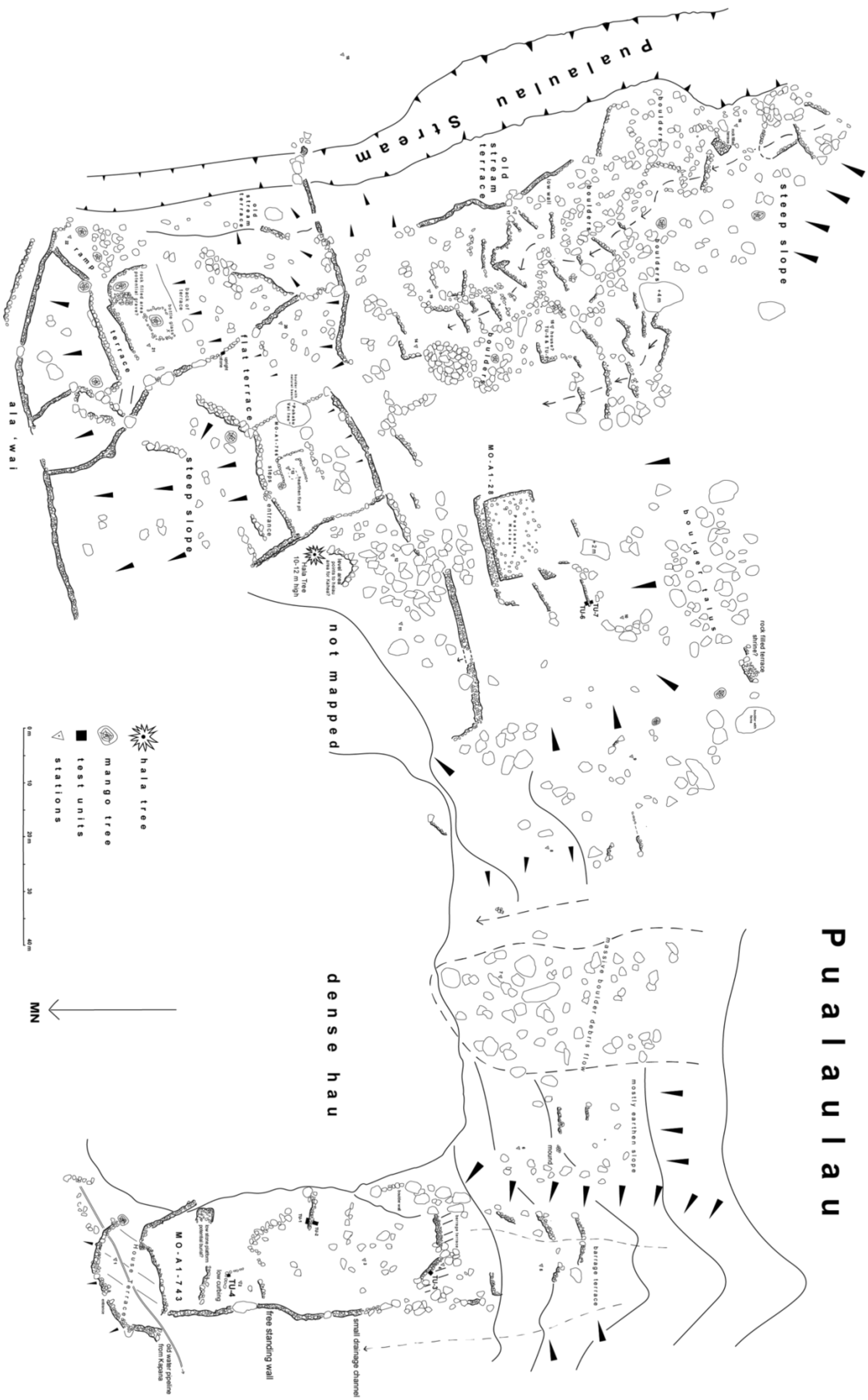

Figure 3. Map of Pualaulau, Hālawa Valley, Moloka'i made by Patrick V. Kirch, used with permission.

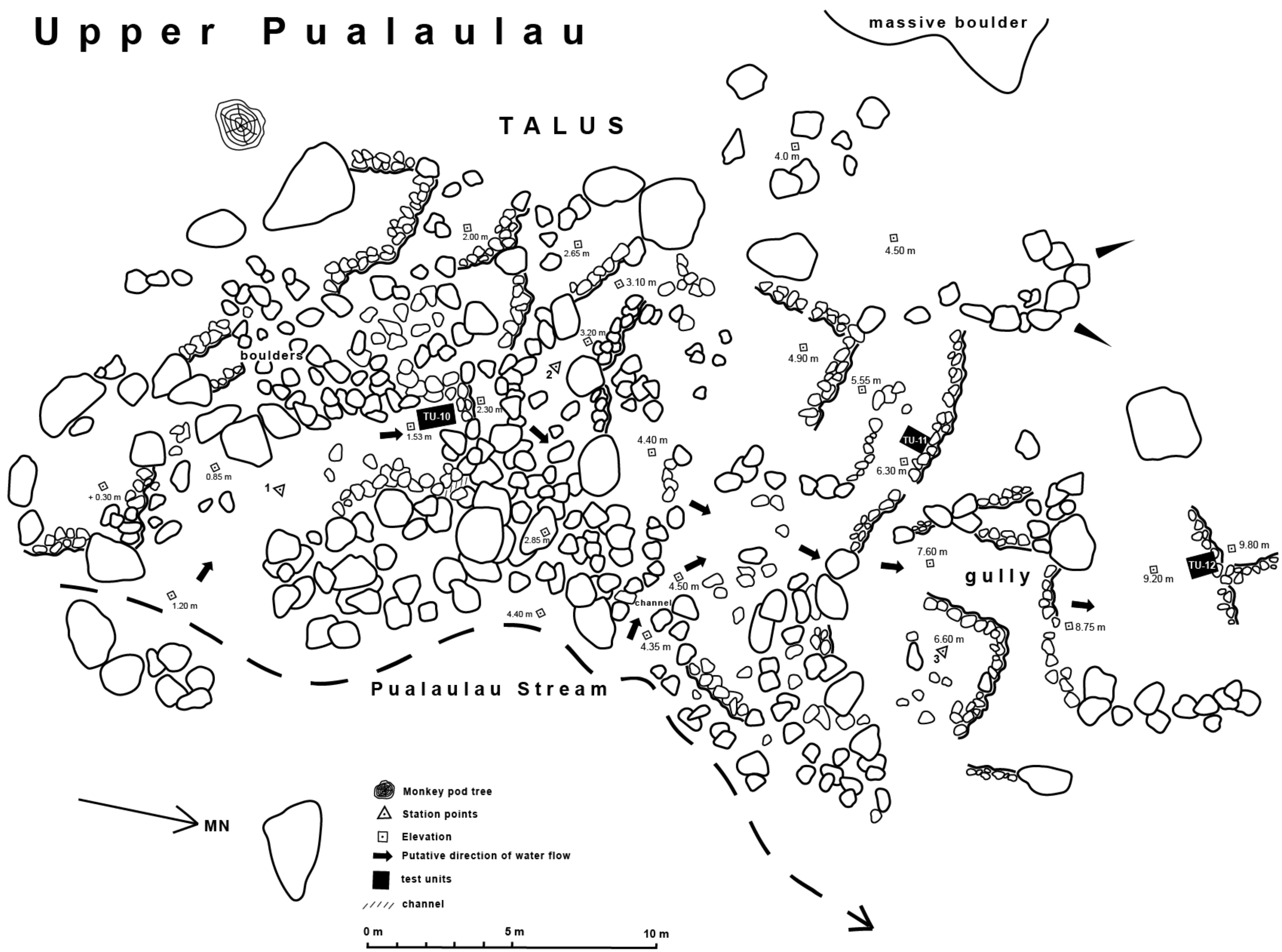

Figure 4. Plane table map of Upper Pualaulau Side Stream Terrace system created by Patrick V. Kirch, used with permission. Test units excavated within the side stream terrace are indicated and labeled accordingly.

TU-10 was excavated in a trench style via natural stratigraphic layers via pick and shovel, and excavation ceased once subsoil had been reached. A stratigraphic profile drawing of the west wall of TU-10 is included (Fig. 5).

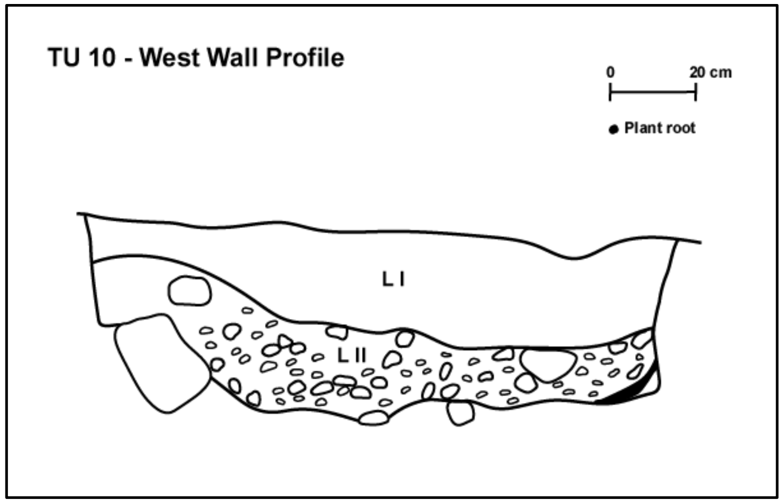

Figure 5. Stratigraphic profile drawing of Test Unit 10

Granulometry samples were recovered from Layer I and Layer II in the west wall profile. Layer I consisted of a very dark brown, soft loamy topsoil, most likely from recent vegetation decay. Layer II was also very dark brown in color, possessing characteristics like Layer I, but with a higher presence of waterworn pebbles and cobbles.

Test Unit 11

A series of well-defined terraces descends downslope from TU-10. TU-11 was placed in the center of this series of terraces, in an area with the most clearly defined retaining wall (Kirch and Swift 2021). This unit had two major stratigraphic layers: Layer I which consisted of soft, fine-grained sediment well-suited for agricultural production, and Layer II, which was like that of Layer I, but with more cobble and rock inclusions.

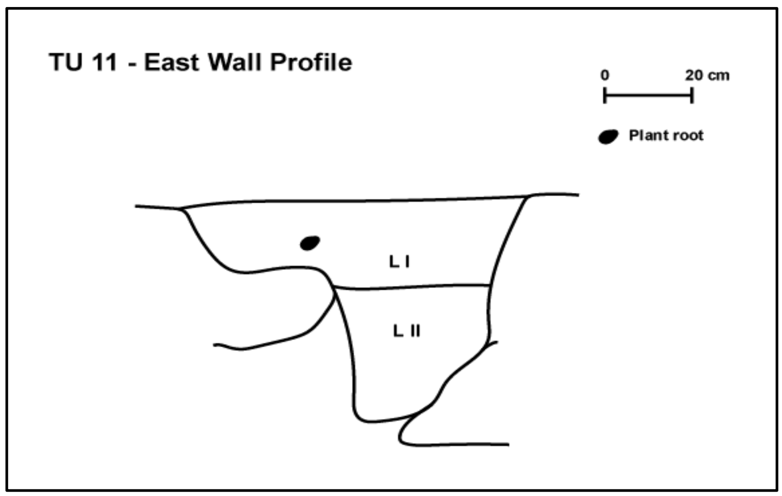

Figure 6. Stratigraphic profile drawing of Test Unit 11

Granulometry samples were taken from both Layer I and Layer II from the east wall profile. A stratigraphic profile drawing of the east wall profile is included (Fig. 6).

Test Unit 12

TU-12 is the third test unit in the side-stream terrace system. This unit was placed downslope of TU-10 and TU-11 in an 'L-' or 'T-' shaped terrace. The unit is located upslope of the perpendicular terrace walls, which might have been used to retain or divert water into other terraces further downslope. Downslope terraces run to the areas west and north of TU-12. The area west of TU-12 might have been walled off to ease in water movement, but surrounding walls and terraces are less defined. The area north of TU-12 is more well-defined, its orientation

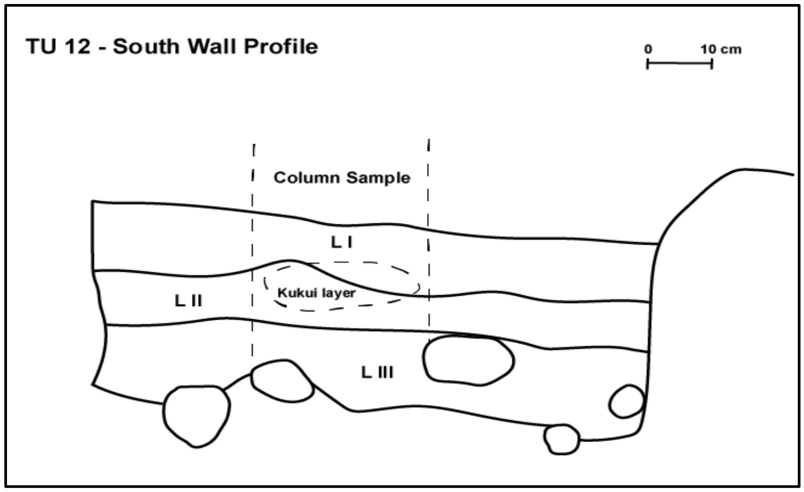

Figure7. Stratigraphic profile of South wall of Test Unit 12

and location within the overall system would suggest more direct water movement or diversion of water throughout the rest of this system via this individual terrace.

Three main stratigraphic layers were identified in this unit, all of which were more like the composition of TU-10 than TU-11. (Kirch and Swift 2021). Layer I was a layer of highly organic material, with a clay like soil texture. Large quantities of kukui nut were uncovered at the interface of Layer I and Layer II, as depicted in the stratigraphic profile drawing. The high presence of kukui nut at the interface of these layers might represent accumulation of organic material during a period of abandonment or low maintenance. Layer II has a much higher presence of small cobbles and pebbles closer to the top of the layer, all of which appear to be subangular or subrounded in shape and surface texture. Several large boulders were exposed at the base of Layer II, with smaller cobble and pebble inclusions that are angular to subangular, which might represent a period of cultivation. Layer III consists mainly of large boulders and gravelly subsoil. Due to the size of the large boulders within the unit, the bases of the main architectural wall stones were not reached.

Granulometry samples were collected from all three layers, from the south wall profile. An additional column sample was taken in 5 cm intervals from the south wall profile to determine changes in soil chemistry as a proxy for agricultural sustainability over time. A stratigraphic profile drawing for the south wall of TU-12 is included (Fig. 7).

Test Unit 13

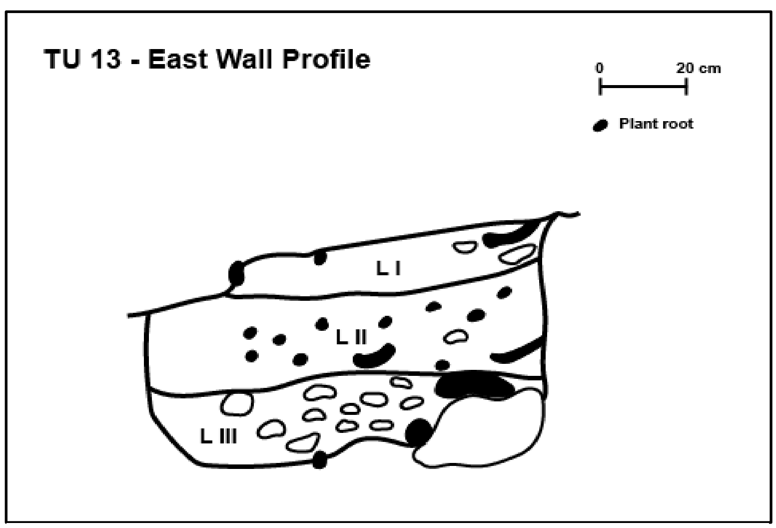

Figure 8. Stratigraphic profile drawing of east wall of Test Unit 13

TU-13 is the fourth excavation in this upper terrace series complex and is situated just upslope of the lowest terrace in this upper Pualaulau system. The unit was originally a 70 cm x 80 cm trench, located in a small but mostly intact terrace (Kirch and Swift 2021). The trench was extended an additional 30 cm in length to accommodate a large boulder occupying the center of the unit, for a total unit length of 110 cm. The boulder was removed from the unit once expansion was complete, with charcoal adhering to and eventually removed and recovered from the underside of the boulder.

Layer I consist of highly organic matter, most likely from recent deposition of colluvial slope and vegetation. The boundary between Layer I and Layer II is highly diffuse, with sediment color appearing lighter in color and soft and loamy in texture as depth increases (Kirch and Swift 2021). Layer III has a color and texture like that of Layer II but has a higher presence of subangular and subrounded cobble and pebble inclusions throughout.

Granulometry samples were taken from all three natural stratigraphic layers in the east wall profile. A stratigraphic profile drawing of the east wall for TU-13 is included (Fig. 8).

Test Unit 14

TU-14 is the fifth and final excavation unit in this upper Pualaulau terrace system. The terrace associated with this unit is the largest and lowest terrace in the system, with a total wall length of approximately 10 m and roughly 3 – 4 rock courses in height. TU-14 is a 150 cm x 100 cm trench running perpendicular to the terrace wall structure, with a maximum depth of 95 cmbs.

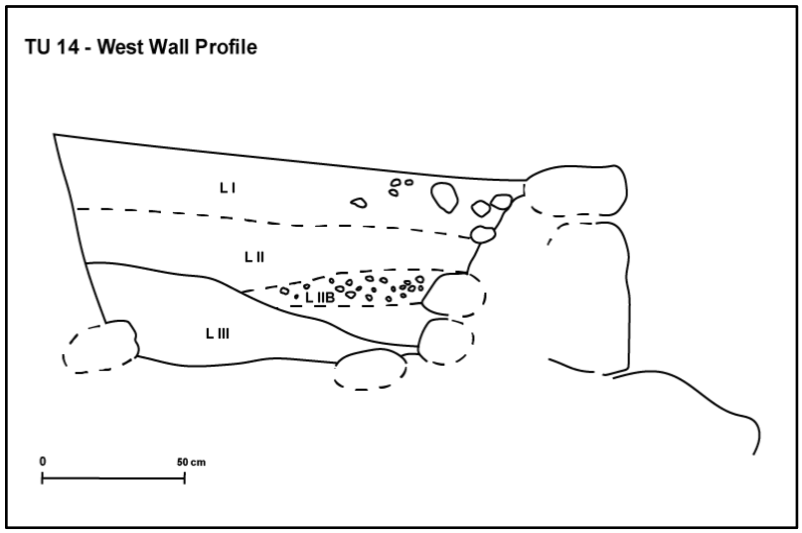

Figure 9. Stratigraphic profile drawing of west wall of Test Unit 14

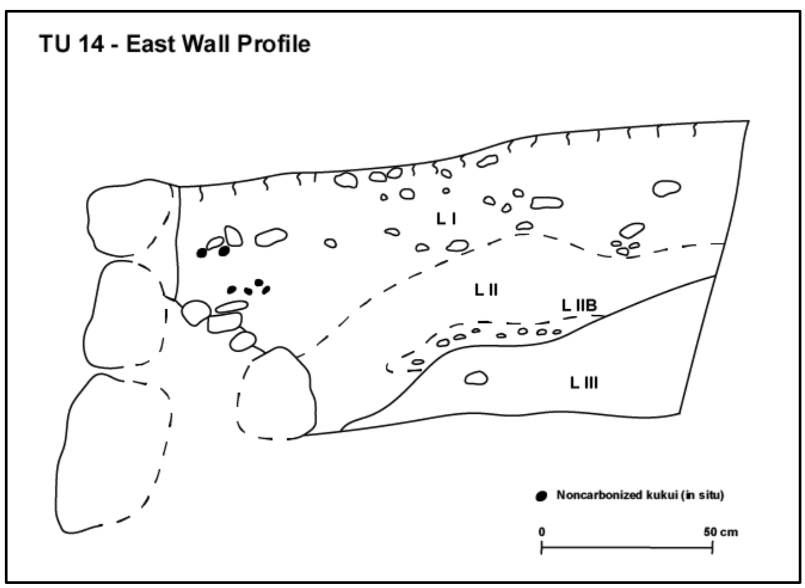

Figure 10. Stratigraphic profile drawing of east wall in Test Unit 14

Sediment in this unit was loosely packed and easier to excavate in compared to other units in this series (Kirch and Swift 2021). Throughout the unit, there are alternating bands of what appear to be subrounded and water worn gravel, which might indicate multiple phases of fluvial deposition and agricultural cultivation. Layer I consist of dark greyish brown sediment, with a distinct angular ped structure (Kirch and Swift 2021) that is diffuse with Layer II. Layer II is a dark reddish gray in color and is silty and sandy in texture, lacking the clay content that is more obvious than Layer I. Layer II has a smaller sub-layer, Layer IIB, which corresponds to the interspersed subrounded colluvial deposits mentioned above. Layer IIB varies across the unit but is visible in both the east and west wall stratigraphic profile drawings. Layer III is dark brown in color and has a soil texture with a higher clay content than Layer I and Layer II and appears to be the colluvial parent material (Kirch and Swift 2021).

Granulometry samples were collected from all layers, including sublayer LIIB, which consists of subrounded potential colluvial sediment depositions. A total of 4 granulometry samples were taken for this unit from the west wall profile. Stratigraphic profile drawings for both east wall and west wall profiles are included (Figures 9 and 10).

The Kapana Tributary-Stream Irrigation System

The Kapana side-stream irrigation system was used as a control against the sediment samples taken in Pualaulau. The ʻili of Kapana is the most mauka ʻili on the south side of Hālawa Valley, just west of Pualaulau. Kapana is divided into two portions by Maka'ele'ele stream, which was used for both irrigated and dryland agricultural systems throughout this area. Both the western and eastern portions of Kapana are decorated with terraces of various sizes, including several large terraces within the lower alluvial flat and smaller terraces like those observed in Pualaulau. Sediment samples were collected from 3 different test units in this area, one from the uppermost portion of the terrace system, one that was centrally located within the system, and one from a terrace located in one of the lower alluvial flats. A plane table drawing of Kapana with location of test units excavated can be seen in Figure 11.

Test Unit 16 and Test Unit 17

TU-16 and TU-17 form a trench across the north and south sides of a well-constructed and intact agricultural terrace at the highest point of the Kapana side-stream system (Kirch and Swift 2021). A plan map drawing of test Unit 16 and Test Unit 17 is show in Figure 12.

Test Unit 16

TU-16 is the first unit in a series of "irrigated agricultural terraces immediately upslope of a large flat alluvial floodplain previously used for loʻi kalo agriculture" in the ʻili of Kapana (Kirch and Swift 2021). This area has more clearly defined terraces and irrigated systems, was previously mapped by Kirch and studied by Riley (in Kirch and Kelly 1975), and offers a good comparison for the side-stream terrace system of Pualaualau.

TU-16 is the uppermost unit located at the highest point of the Kapana side-stream terraced irrigation system(Kirch and Swift 2021). TU-16 is a 70 cm x 80 cm with a maximum depth of 40 cmbs located on the upslope side of this uppermost terrace wall. At 30 cmbs a large flat boulder was uncovered at the center of the unit, making it difficult to excavate the remainder of the unit. The excavation of TU-16 ceased once the area surrounding the boulder was leveled.

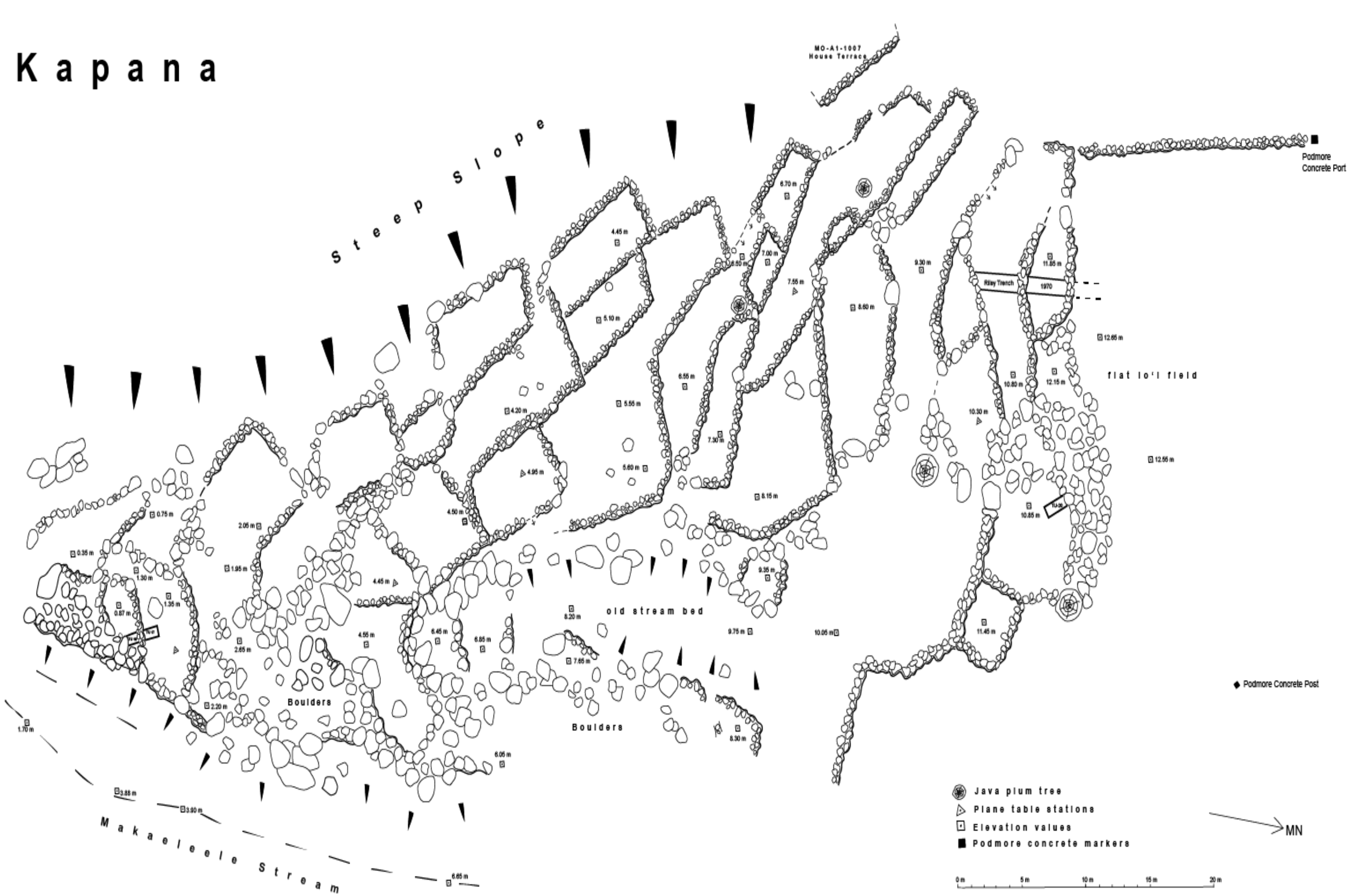

Figure 11. Plane table map of Kapana Tributary Stream Terrace system created by Patrick V. Kirch, used with permission. Test units excavated within the side stream terrace are indicated and labeled accordingly.

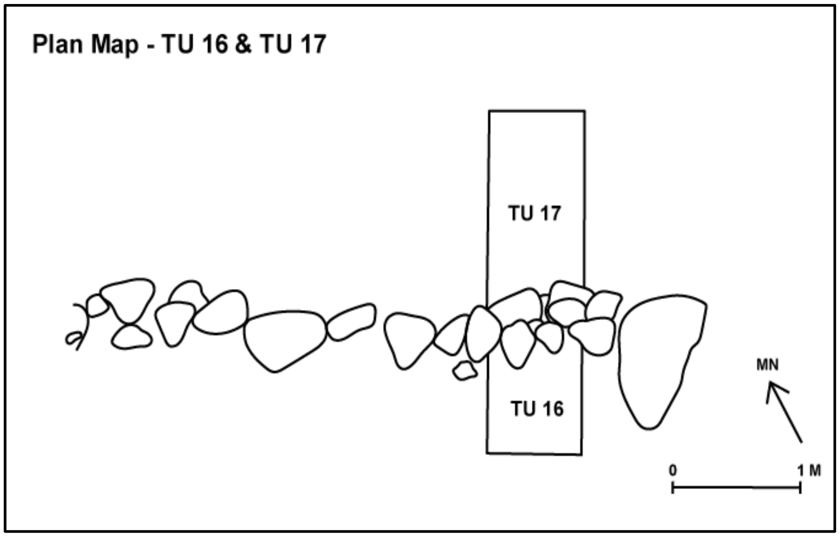

Figure 12. Plan map of Test Unit 16 and Test Unit 17

TU-16 was excavated according to natural stratigraphic layers with pick and shovel and has three main stratigraphic layers. Layer I is a loosely compact, highly organic material that most likely represents a recent layer of topsoil deposition. Layer II is more compact, clay-like sediment that contained large quantities of charcoal, most likely the main cultural deposit. Layer III has a texture and composition like Layer II but contains a high number of cobbles and rock inclusions that increase angularity as depth increases.
Granulometry samples were collected from all three stratigraphic layers, specifically from the east wall profile. A stratigraphic profile drawing of the east wall is included (Fig. 13).

Test Unit 17

TU-17 is situated on the downslope side of the uppermost intact terrace wall. The unit is 75 cm x 125 cm with a maximum depth of 65 cmbs. This unit has three distinct stratigraphic layers that correspond to multiple periods of use, like what was observed in several of the irrigated terraces in Pualaulau (Kirch and Swift 2021).

Layer I has a clay sediment texture with large amounts of waterworn and subrounded pebbles and cobbles. The gravelly composition suggests that this layer was deposited fluvially. Layer II is a finer sediment texture with a higher clay content than Layer I (Kirch and Swift 2021). This layer contains some large rock inclusions and minimal amounts of subrounded or waterworn pebbles. Large amounts of unburnt kukui nuts were found throughout the unit; an obvious ‘kukui lens’ was identified and excavated as a separate level within Layer II. Layer III is like Layer I, with a clay content somewhere between Layer I and Layer II. Large amounts of waterworn pebbles were observed towards the surface of Level III, with larger and more angular cobbles towards the bottom of the unit.

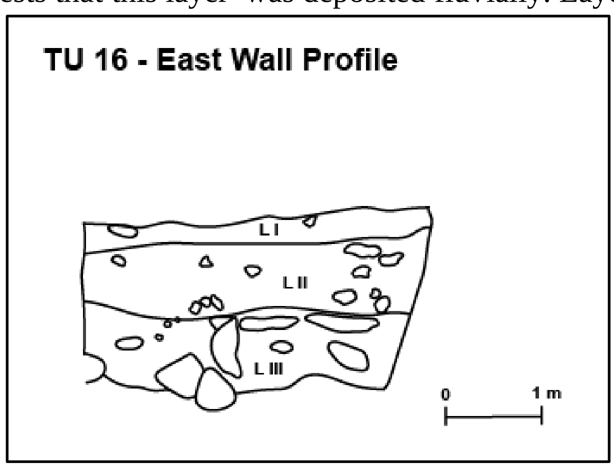

Figure 13. Stratigraphic profile drawing of east wall in Test Unit 16

TU-17 had a similar stratigraphy to that of TU-14, with distinct natural layering of fluvial deposits. This suggest that there might be periods of agricultural cultivation followed by periods of abandonment and potential sediment deposition via hydraulic movement.

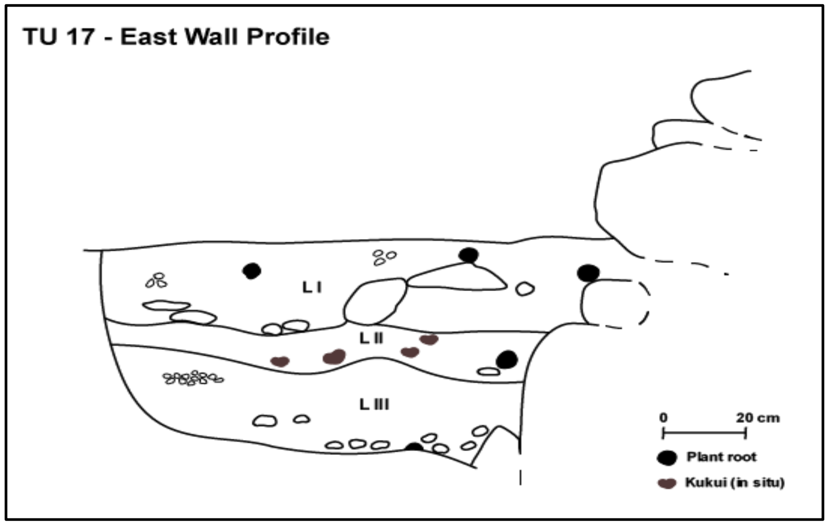

Figure 14. Stratigraphic profile drawing of east wall in Test Unit 17

Granulometry samples were collected from all three stratigraphic layers from the east wall profile. Additionally, environmental samples and sediment samples were collected for environmental reconstruction and long-term sustainability of terraced agricultural systems. Stratigraphic profile drawings for east wall profile is included (Figures14).

Test Unit 20

TU-20 is a 60 cm x 150 cm trench oriented perpendicular to the lowest terrace of the Kapana side-stream irrigation system. This unit was placed upslope and abutting a built up and fairly intact terrace wall, just above the large pond fields of the adjacent alluvial flat (Kirch and Swift 2021).

Excavation occurred according to natural stratigraphic changes until a deposit of boulders was reached at a maximum depth of 45 cmbs. Given its location at the base of this larger irrigated terrace system, we expected the cultural deposits in this unit to be like TU-14, however the unit was surprisingly shallow. There were 4 distinct stratigraphic layers within this unit, none of which were like those found in any of the Pualaulau test units. Layer I consisted of a thin layer of rich, darkly colored, organic topsoil that was loamy in texture, ideal soil for cultivation. Layer II consists of a dark brown, finer silty clay sediment with

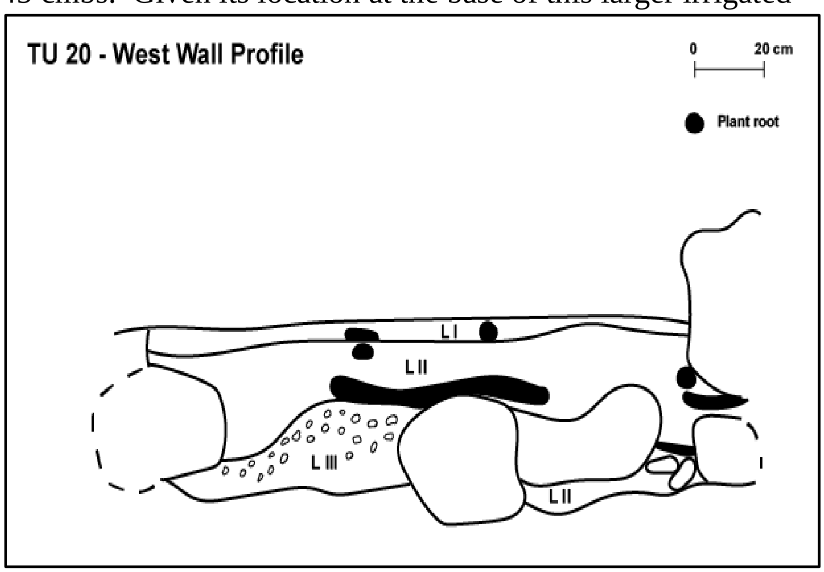

Figure 15. Stratigraphic profile drawing of west wall in Test Unit 20

minimal rock inclusions and vegetation. Layer III consists of a dark brown sediment like that of Layer II but has a higher number of subangular rock inclusions that were absent in the upper layers. Layer IV is a fine, looser, silty loam textured sediment only visible on the south end (are furthest away from wall facing) of the test unit. High amounts of charcoal and other cultural materials were recovered from this area of the TU-20 and were noticeable in the east wall profile (Figure 15).

Granulometry samples were taken from Layers I, II, and III from the west wall profile. A stratigraphic profile drawing for the west wall profile of this unit was included.

Laboratory Analysis

Results from particle size analysis and determination of angularity will be combined for each section, beginning with an analysis of each control sample followed by a discussion of results from each individual unit.

Control Samples

Granulometry or Particle Size Analysis

Granulometry samples have been given a unique ‘Sample ID’ that reads in the following order: Site Area, ‘ili name, TU-#, and Layer. Control samples were denoted as the following: Colluvial Slope Control (CSC), Inlet 1 Upper Stream Control (UIC1), Inlet 2 Down Stream Control (DSC2), and Stream Bed Control (SBC). A complete ‘Sample ID’ would read as the following: “HALPUATU14LIIB”, which is to be read as ‘Hālawa Valley, Pualaulau, TU14, Layer IIB’. Each of the control samples should present a different distribution of sediment particles, with the colluvial slope control and the stream bed control samples falling on opposite ends of the spectrum and the two inlet irrigated samples being somewhere along that scale.

The colluvial slope control sample (CSC) has high values for larger particles with phi sizes -2, -1, and 1 (all material > 0.5 mm in size), and with only small amounts of material < 0.5 mm in size. The sediment particle size distribution for the CSC sample can be seen in Figure 15A. The stream bed control sample (SBC) had lower values for larger particles with phi sizes -2 and -1 and overall higher values for smaller-sized particles with phi sizes 1, 2, 3, 4.05, and 6, corresponding to those in the sand, silt, and clay categories. The sediment particle size distribution for the SBC sample can be seen in Figure 15B. The upper inlet control sample (UIC1) has a particle size distribution similar to that of the SBC sample, but has the lowest values for phi size -2, but the highest values for phi sizes 1 and -1. The sediment particle size distribution for the UIC1 sample can be seen in Figure 15C. Distribution for finer grain sediment in the UIC1 (sediment < 0.5 mm) has a similar distribution to that of the SBC sample. The lower inlet control sample (DSC2) has a sediment particle size distribution similar to that of the CSC sample, with high values of larger particles and minimal amounts of finer grained sediment. The DSC2 sample has the lower values of fine-grained sediment (particles <0.5 mm) and the highest amount of larger grained samples, even when compared to the CSC sample. The sediment particle size distribution for the DSC2 sample can be seen in Figure 15D. The particle size distribution for all control samples can be identified in Figure 16.

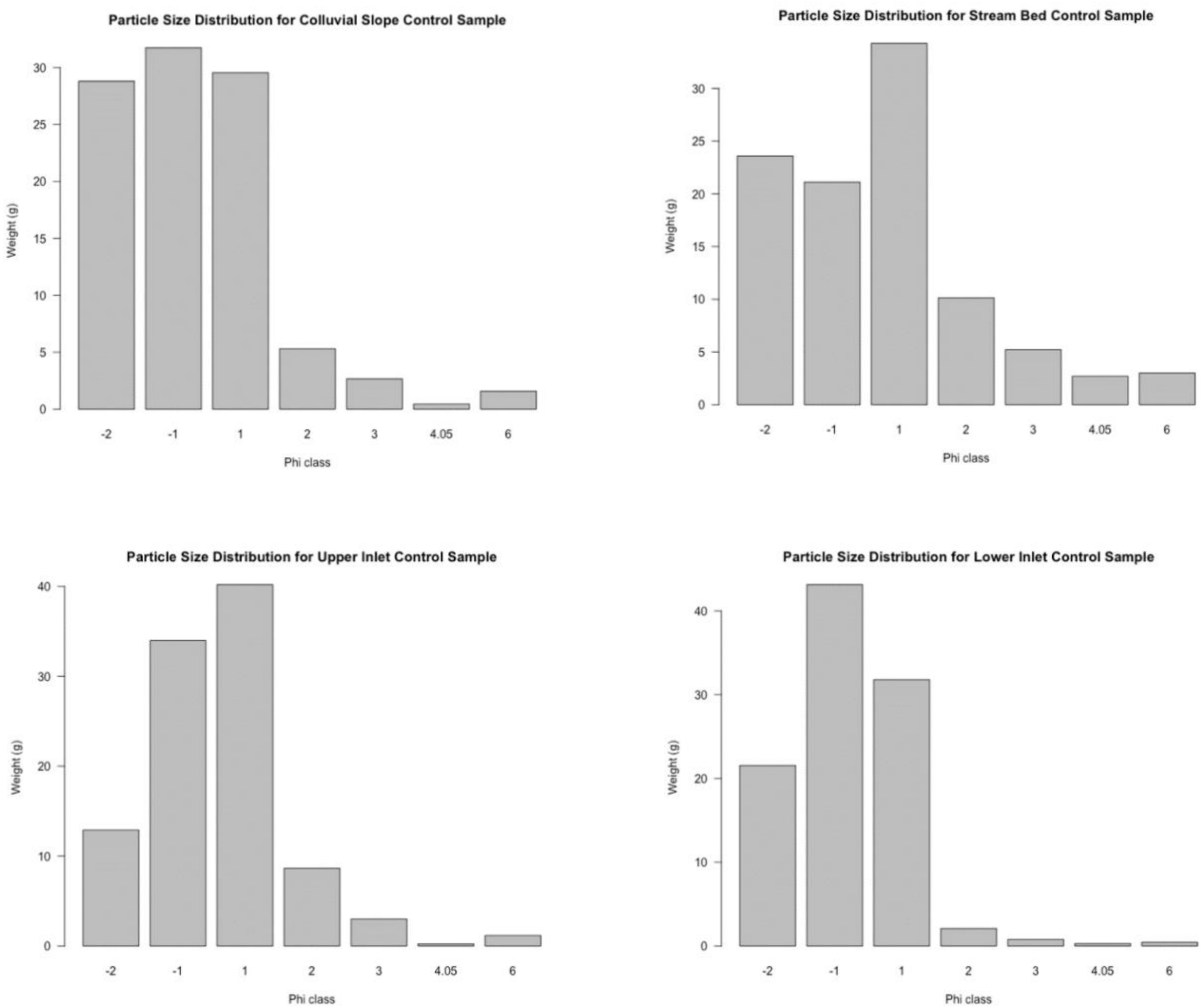

Figure 16. A) Particle size distribution for colluvial slope control sample. B) Particle size distribution for stream bed control sample. C) Particle size distribution for upper inlet control sample. D) Particle size distribution for lower inlet control sample. Phi class on x-axis, weight of sample (g) on y-axis.

Determination of Angularity

Angularity of sediment particle sizes for class size 2mm – 4mm were determined for each sample using Powers ordinal classes (1953). Angularity was classified on a scale from 1 – 6, with 1 being ‘very angular’ and 6 being ‘very rounded’ in shape. A total of 100 randomly selected sediment particles were assessed for angularity. A general classification was given to the entire sample based on sub-sampling classification.

Control Samples at 2mm – 4mm

In theory, each control sample should exhibit a different degree of angularity. For samples that are found in the colluvial slope, we expect to have higher amounts of sediment particles that are more angular in shape as opposed to the stream bed control sample, where we expect to have higher amounts of sediment particles that are more rounded in shape. Sediment that is transported in sudden, low energy events, specifically those that are the result of a landslide or rock fall, tend to have more angular ped structures. Sediment that is transported fluvially is often rounded due to water caused weathering. For the two stream inlet samples we expect to see a mix of values of sediment particles that are angular, subangular, subrounded, and rounded in shape. Sediment particle shape can be influenced by depositional means, with colluvial sediment peds being more angular in shape and fluvially transported sediment beds being more rounded.

As can be seen in Figure 16A, the CSC sample has high levels of very angular and angular sediment particles, with very few particles classified as subangular. The CSC sample has been classified as very angular-angular in sediment particle shape. The UIC sample has varying values of sediments with different classifications, the highest being angular, followed by subangular, and some subrounded sediment particles. Given that this sample should be characteristic of intermittent irrigation, the distribution of angular, subangular, and subrounded particles is accurate for this sample. The UIC sample has been classified as angular-subangular in shape. The lower inlet or DSC sample has a distribution different from the UIC sample, with higher amounts of subangular sediment particles, followed by angular, and subrounded classifications. As a unit the DSC sample can be classified as subangular-angular in sediment particle shape.

The DSC is expected to have a similar sediment particle distribution as the UIC sample given that they both are reflective fluvially transported sediment. It is likely that the DSC sample reflects more fluvial input, or a higher flow rate given that there are more subrounded sediment particles in this sample than in the UIC sample. The SBC control had more variation in its sediment particle shape classification, having primarily subrounded and subangular sediment particles. The SBC sample has more variation in particle shape than any other control sample, which is surprising but also to be expected. The SBC sample was taken directly from the Pualaulau Stream bed, which should contain primarily subrounded and rounded particles, but as new colluvial material is transported or falls into the stream bed, there should be some smaller sediment particles that are more angular in shape. As a unit the SBC can be classified as subrounded-subangular in sediment particle shape. Distributions of sediment shape classifications for all control samples can be found in Figure 17.

Selected Samples from Excavated Contexts

Selected samples were chosen for further analysis based on distribution similarity to one of the four control samples. Of the 30 samples, only 11 had a particle size distribution identical to one of the control samples. This similarity was based on raw data values as well as histogram plot distribution of all granulometry samples. Those selected samples are described in depth in the following section.

All sediment samples were selected for angularity classification and then compared to the distribution for all control samples. Angularity for each sample was determined based on the two highest grades for each sample. Distribution for all samples were also compared to and classified based on likeness to control samples.

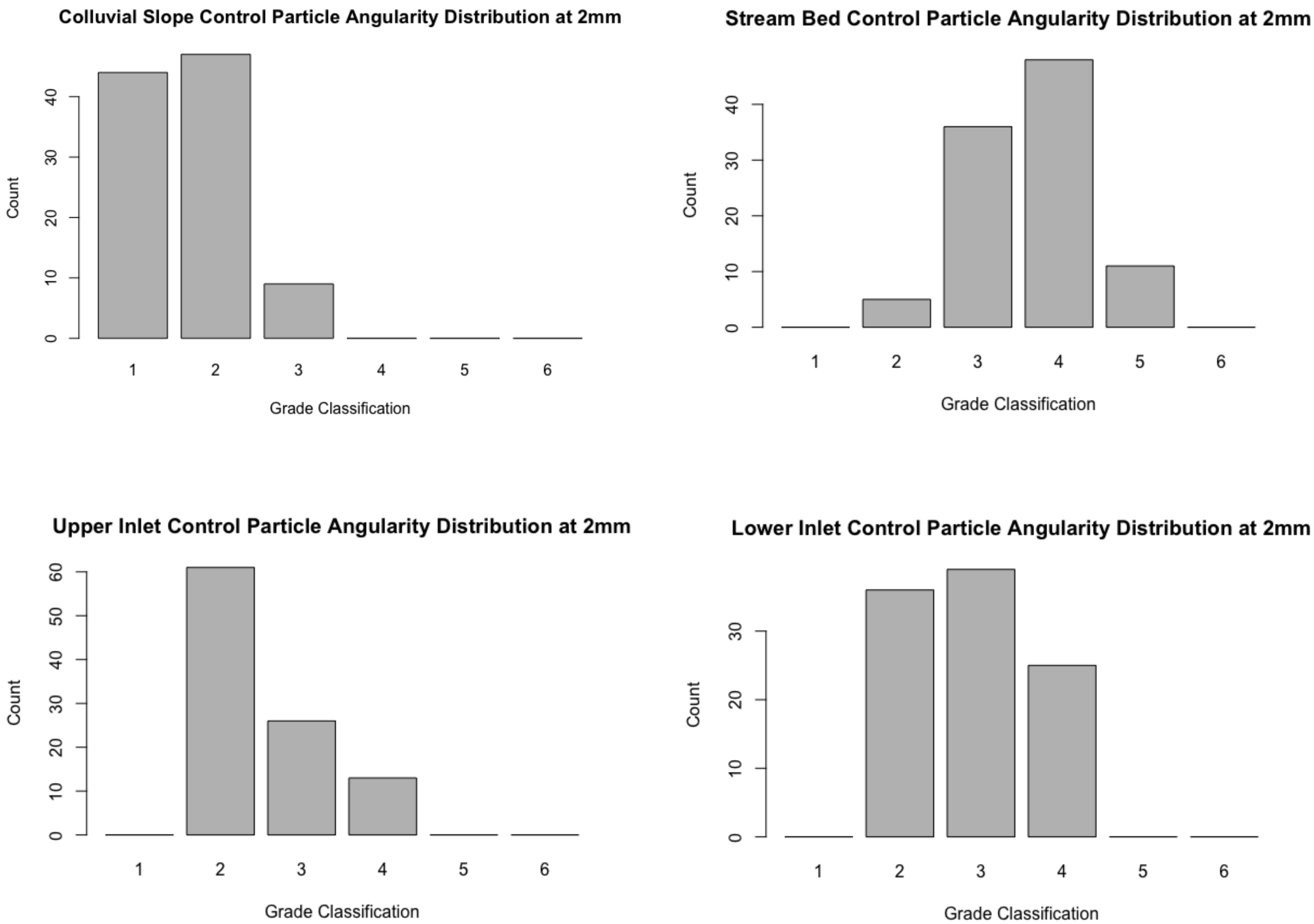

Figure 17. A) Bar graph that demonstrates colluvial slop control particle angularity distribution at 2mm. B) Bar graph that demonstrates stream bed control particle angularity distribution at 2mm. C) Bar graph that demonstrates upper inlet control particle angularity distribution at 2mm. D) Bar graph that demonstrates lower inlet control particle angularity distribution at 2mm. Grade classification on x-axis, particle count on y-axis.

Colluvial Slope Comparison

Particle Size Analysis

Five granulometry samples displayed particle size distribution similar to the CSC sample, including samples from TU-10, TU-11, TU-17, and two samples from TU-20. The granulometry sample from TU-10 Layer I, reflects a similar particle size distribution to that of the CSC sample, with large values for phi class sizes -2,-1, and 1, and low values for all other phi class sizes. TU-10 is the uppermost test unit placed in the Pualaulau side stream irrigation system, which we expected to have a particle size distribution more like that of the SBC sample. This distribution might be due to the sample coming from the surface or topsoil layer, which most likely reflects more recent sediment deposition.

The granulometry sample from TU-11 Layer II was also taken from an upper unit located in the Pualaulau side stream irrigation system. Layer II is loamy in texture with small rock inclusions throughout and might have served as good cultivation material. This sample also had high values for phi size -1 (2mm – 4mm), which suggests that larger, more angular clastics were most likely transported via erosional deposition with minimal fluvial movement.

TU-17 Layer II presented a similar particle size distribution to the granulometry samples previously discussed in this section, with high values for larger sediment particles and minimal values for fine grained sediment. Unlike the samples discussed thus far, TU-17 is one of the first units placed in the irrigated side-stream terrace system in Kapana. The location of this unit is on the downslope side of one of the uppermost terrace walls, closest to the stream. Layer II contained a large unburnt 'kukui nut' lens that was present in the east wall profile. The sediment particle size distribution and presence of a kukui lens supports the idea that this layer represents a period of abandonment or general accumulation of sediment and vegetation.

The final two samples that have a similar particle size distribution to the CSC sample come from Layers II and IV from TU 20. This unit is the lowest unit in the Kapana irrigated side-stream terrace system, in one of the largest terraces just above the alluvial flat pond fields. Layer II was silty and loamy in texture, with minimal rock inclusions. The lack of rock inclusions, subangular or subrounded, suggest that this layer might have been used for agricultural production. The similarities to the CSC suggest that the Kapana system was constructed on a colluvial rather than the terrace being constructed of material that was fluvially transported. The granulometry sample from Layer IV presented a similar composition to Layer II but is slightly siltier in texture. This layer was only present in the southern end of this unit and yielded a cultural deposit

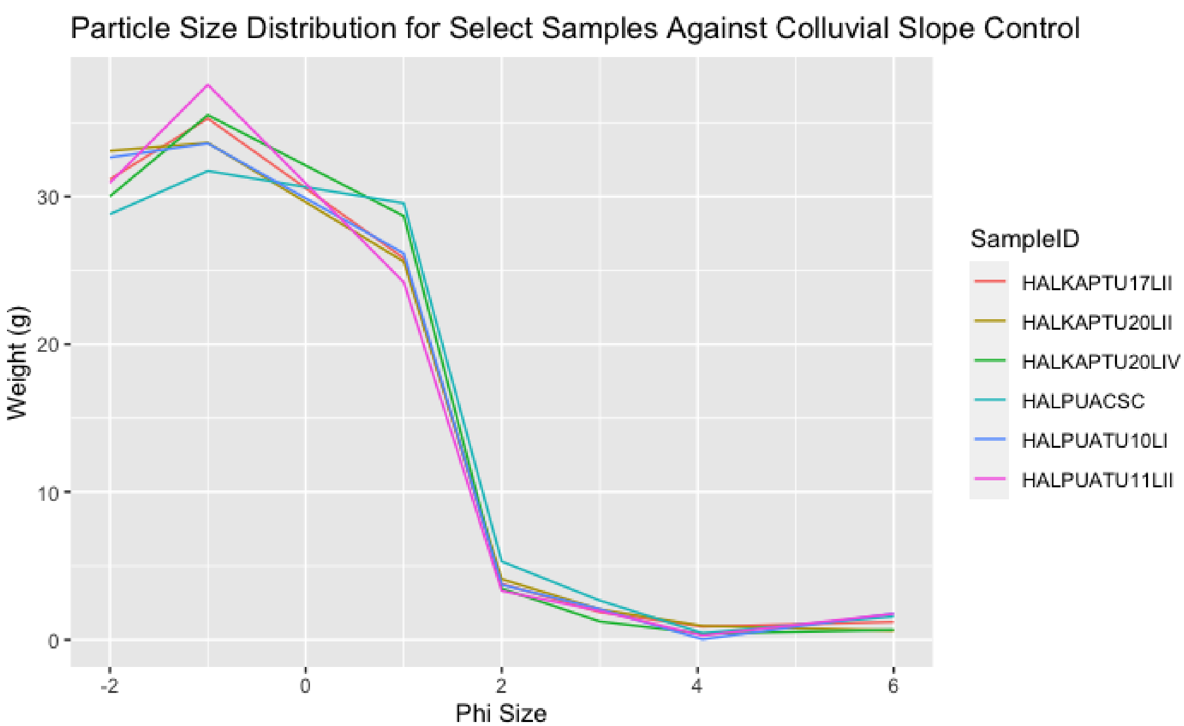

Figure 18. Distribution of particle size distribution for selected samples against the colluvial slope control (CSC) sample.

including charcoal, lithic flakes, and burnt kukui nut. This layer might represent a period of habitation on this slope prior to construction of the side-stream irrigation system. This particle size distribution is consistent with the CSC sample rather than with fluvial deposition.

Figure 18 displays the sediment particle size distribution for the previously discussed samples.

Grade of Angularity

Two sediment samples showed similar sediment angularity distributions to the CSC sample. The first sample that has a similar sediment particle angularity comes from TU3, Layer I. The sediment sample from TU 20, Layer II also has a sediment angularity distribution like that of the CSC sample. The TU20 sample has most of its sediment particles falling into classes 1,2, and 3, with <10 sediment particles falling into the class 4. Based on the similarities between the CSC samples and those taken from TU-20, it is most likely that this terrace was constructed out of the original colluvial parent material, most likely as some habitation site given its location. It was then adapted for use in the Kapana side-stream irrigation system, but due to its downstream location, was not as greatly impacted by fluvial movement and deposits, like those further upslope. While this terrace may have been adapted for irrigation, the sediment distribution and angularity of sediment particles reflects that of the parent material.

Downstream (Inlet 2) Comparison

Particle Size Analysis

Six granulometry samples displayed similar sediment particle size distributions to the down-stream inlet (DSC) or lower inlet control sample, including two samples from TU-12, one sample TU-13, and two samples from TU-16.

TU-12 yielded two samples with a similar distribution to that of our DSC sample and is one of the five test units placed in the upper Pualaulau side-stream terrace system. This test unit is in the middle of the system, so in theory could have been used for agricultural purposes or as a water diversion area. The granulometry sample from Layer I is dark and organic in composition, with a high clay content. There is a kukui nut lens that crosses the interface between Layer I and Layer II. This suggests that there might be a period of abandonment, low maintenance, or in wash from hydraulic movement. The granulometry sample from Layer II was also included in this comparison. The sample had < 100 g in total, so although the raw values are not the same, the trends in distribution are similar enough to resemble the DSC sample. Layer II is silty and loamy in texture and contained large amounts of subangular and subrounded cobbles and pebbles. Both samples have similar distributions for the finer grained particles that have not been observed in other samples collected from this terrace system. that have not yet been observed.

TU-13 is located in the upper Pualaulau side-stream system and yielded a granulometry sample that was like that of the DSC sample. Layer III was loamy in texture with a high concentration of subangular and subrounded pebbles and cobbles. The high presence of rock inclusions at the base of this layer is suggestive of one or more events that allowed for the transport and distribution of these larger particles. The overall particle size distribution for this layer has a similar trend to that of the DSC sample, with lower numbers of particles > 4mm and higher values for particles between 2mm – 4mm in clast size.

The remaining two granulometry samples that most closely reflect the DSC distribution come from Layers I and II of TU-16. This test unit is the uppermost unit of the Kapana side-stream irrigated terrace system and is located adjacent to the uppermost intact terrace wall. Layer I had a sediment particle size distribution that was most like that of the DSC sample, with relatively similar quantities for all phi class sizes. This Layer was silty clay in texture, with minimal rock inclusions and organic material. The similarities in distribution between this sample and the DSC sample suggest that this most recent deposition might also have been via fluvial movement. The granulometry sample from Layer II also displayed a similar particle size distribution, with high amounts of particles in the -1 phi class size (2mm – 4mm) and a relatively even distribution of sediment of finer classes.

Sediment particle size distribution for each of the discussed samples are in Fig. 19.

Grade of Angularity

The DSC sample has a general sediment angularity that can be classified as subangular-angular. Seven of the sediment samples demonstrate a sediment particle angularity distribution like that of the DSC sample. This includes samples from TU 11, TU 13, TU 14, TU 17, and TU 20.

The first two samples come from TU 11, one from Layer I and the other from Layer II. The sample from Layer I has a distribution of sediment particles that fall in angularity classes 2 and

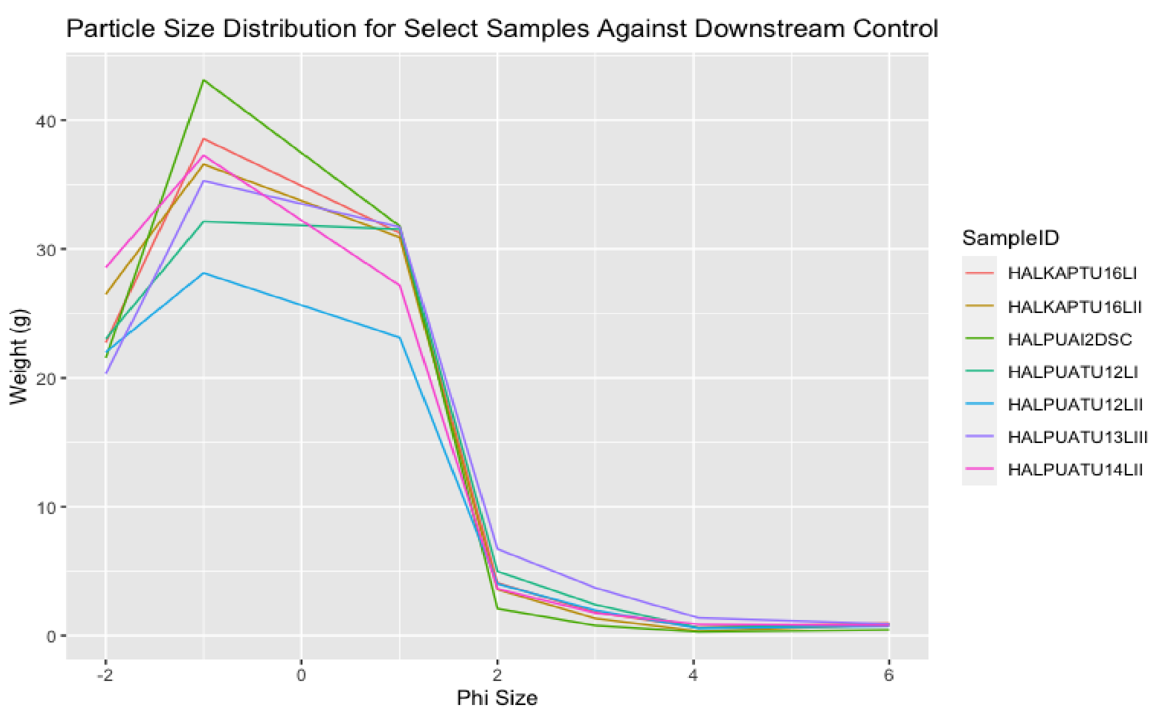

Figure 19. Distribution of particle size distribution for selected samples against the downstream control (DSC) sample.

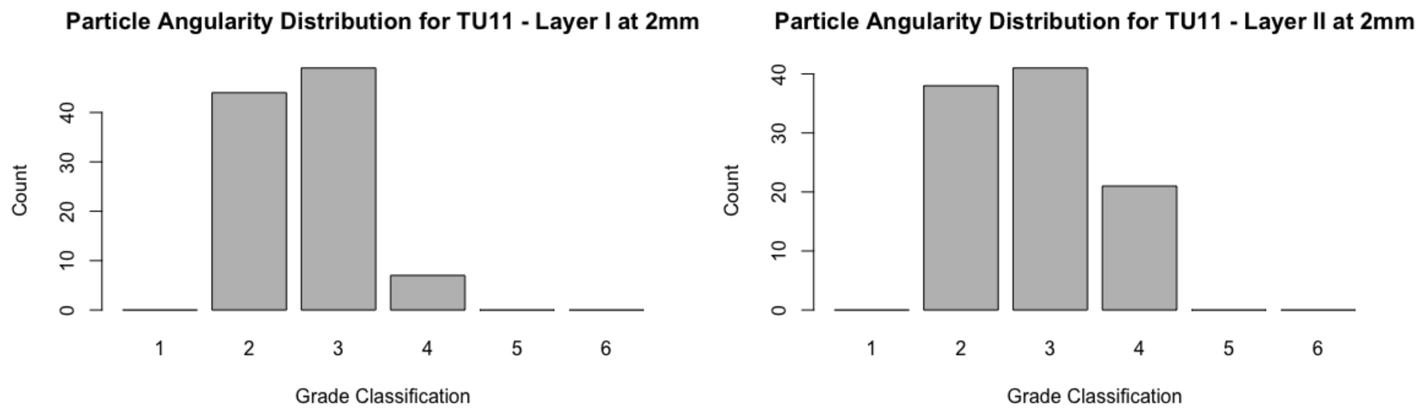

Figure 20. A) Bar graph that demonstrates sediment particle angularity distribution for TU11 Layer I at 2mm. B) Bar graph that demonstrates sediment particle angularity distribution for TU11 Layer II at 2mm. Grade classification on x-axis, particle count on y-axis.

3, with < 10 particles falling into class 4. The sediment from this layer can generally be classified as being subangular-angular in shape. The second sample from TU 11 comes from Layer II, which has a sediment particle angularity distribution that fall within angularity classes 2,3, and 4. While there are more sediment particles that fall within the 'angular' category as opposed to the 'subrounded' category, this layer can be generally classified has having a subangular-subrounded sediment particle shape. This classification is based on the ratio of rounded-angular sediment particles. Distributions for sediment samples from TU 11 can be found in Figures 20A. and 20B.

Sediment samples from TU 13 and 14 also demonstrate sediment particle angularity distributions like the DSC sample. The TU 13 sample comes from layer II and has particles that primarily fall into class 2, 3, and 4. The majority of the sediment particles fall into the subangular-subrounded categories, so this layer can generally be classified as having a subangular-subrounded sediment particle angularity. Two sediment samples from TU 14 also displayed sediment particle angularity distributions like the DSC sample. The sediment sample from TU 14, Layer I has a distribution that is most like the DSC sample, with sediment particles falling into classes 2, 3, and 4. This layer can be generally classified as having sediment that is subangular-angular in shape. The sediment sample from TU 14, Layer II also demonstrates a similar distribution, with most particles falling within classes 2, 3, and 4. Sediment from this layer can be classified as subrounded-subangular in sediment particle shape. While Layers I and II are classified as different angularity classes, they both demonstrate some hydraulic deposition of sediments in these layers. Distributions for sediment samples from TU 13 and TU 14 can be found in Figures 21A, 21B, and 21C.

The final two samples that most closely resemble the DSC sample are from TU 17 and TU 20. The sample from TU 17 comes from Layer II with most of these sediment particles falling in classes 2, 3, and 4. Most particles for this sample fall into classes 3 and 4, with < 10 particles falling into class 2. Based on this distribution, TU 17 Layer II can be generally classified as having a subrounded-subangular particle shape. The final sample in this groups comes from TU 20, Layer III. This sample has a sediment particle angularity distribution that trends more towards angular than rounded. Most particles from this sample fall into classes 2 and 3, with <

10 sediment particles in class. Based on this distribution, sediment from TU 20, Layer III can be classified as subangular-angular is shape.

Stream Bed Comparison

Particle Size Analysis

The final granulometry sample that displayed a particle size distribution most like the SBC sample also came from TU-16. This unit is the upper most unit in the side-stream irrigation system located in Kapana. The unit was placed on the upslope side of the uppermost intact terrace wall in this system. Two samples from this unit already displayed sediment particle size distribution like the DSC, so it is interesting that a third sample also reflected distribution similarities to the SBC sample.

Layer III of TU-16 was loamy and clay-like in texture like Layer II but has an higher frequency of subangular and subrounded rock inclusions. The sediment became more mottled and angular in shape towards the bottom of this unit, but subsoil was not reached. The granulometry sample from Layer III has a similar distribution of sediment particles < 2mm in size. Although the SBC sample has higher levels of particles of phi class -1 (2mm – 4mm), the remaining values for all other class sizes have comparable trends.

Grade of Angularity

There are 12 sediment samples that have a similar sediment particle angularity as the SBC sample. These samples come from TU 10, TU 12, TU 13, TU 14, TU 16, and TU 17 – providing a range of samples from both Pualaulau and Kapana.

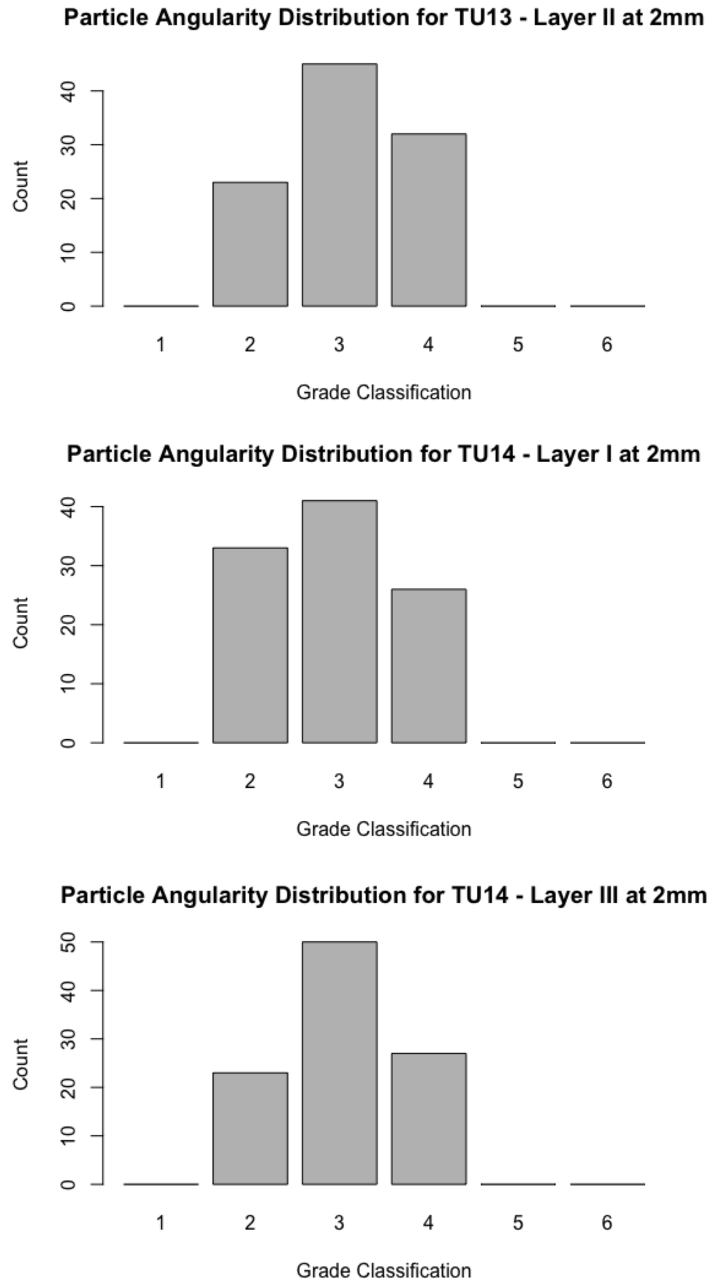

Figure 21. A) Bar graph that demonstrates sediment particle angularity distribution for TU13 Layer I at 2mm. B) Bar graph that demonstrates sediment particle angularity distribution for TU14 Layer I at 2mm. C) Bar graph that demonstrates sediment particle angularity distribution for TU14 Layer II at 2mm. Grade classification on x-axis, particle count on y-axis.

The first set of samples come from TU 10, the uppermost unit from the Pualaulau side stream terrace system. Samples from Layer I and Layer II both displayed similar sediment particle angularity distribution to the SBC sample. Sediment from both Layer I and Layer II have sediment particles falling within class 3 and 4, being primarily subangular and subrounded. Both samples had similar distributions, with more sediment particles falling into class 4 than 3. Given this distribution both layers can be classified as having a subrounded-subangular sediment particle shape indicative of fluvial transport.

All three layers from TU 12 displayed a sediment particle shape distribution like that of the SBC sample. Layer I has a distribution that leans towards the rounded end of the spectrum. Sediment particles from this sample fall within classes 3, 4, and 5. The majority of sediments fall within the class 3 category and decrease in number as class level increases. Layer I can generally be classified as having a subangular-subrounded sediment particle shape. Layer II has a distribution that is more normal in shape, with most sediment particles falling into class 3, < 20 sediment grains falling into class 2, and < 10 sediment grains falling into class 4. Given this distribution, Layer II can be classified as subangular in sediment particle shape. The final sample from Layer III has the most varied distribution out of all samples analyzed. The sediment

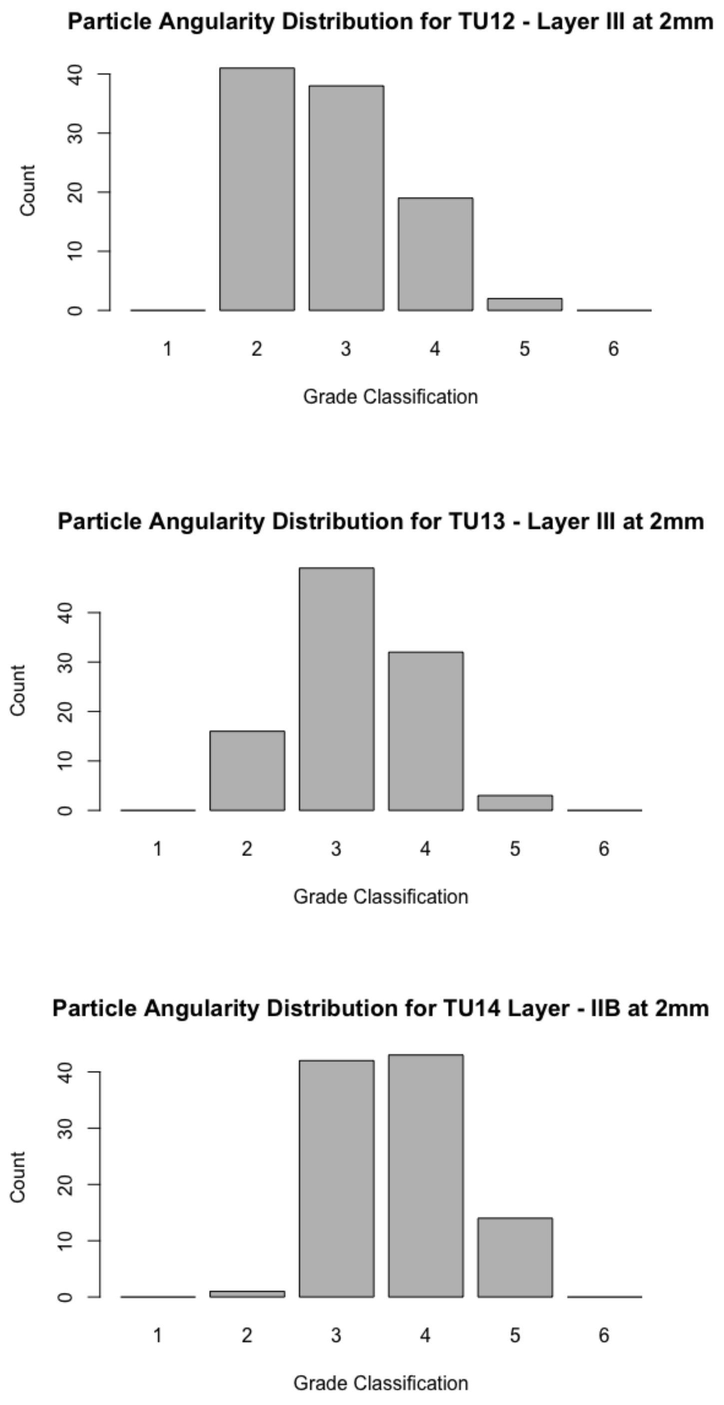

Figure 22. A) Bar graph that demonstrates sediment particle angularity distribution for TU12 Layer III at 2mm. B) Bar graph that demonstrates sediment particle angularity distribution for TU13 Layer III at 2mm. C) Bar graph that demonstrates sediment particle angularity distribution for TU14 Layer IIB at 2mm. Grade classification on x-axis, particle count on y-axis.

grains for this sample fall into classes 2, 3, 4, and 5, in descending order. Most of the sediment particles for this sample fall into class 2 and 3, with < 20 sediment particles falling into class 4, and < 10 sediment particles falling into class 5. While there are many angular sediments particles observed in this sample, the ratio of subangular/subrounded/rounded sediments allows for this layer to be generally classified as subangular. Distribution for this sample can be found in Figure 22A.

The next two samples come from TU 13 and TU 14 which are the two units in the lowest terraces in the Pualaulau side stream system. The TU 13 sample comes from Layer III and has a sediment particle shape distribution that leans towards the rounded end of the classification scale. Most of the sediment particles from this layer fall into classes 3 and 4, with < 20 sediment particles falling into class 2, and < 10 particles falling into class 4. Given the distribution of this sample, the layer can be generally classified as subangular-subrounded in particle shape. Distribution for sediment particles from TU13, Layer III can be found in Figure 22B.

The TU 14 sample comes from Layer IIB, which corresponds to the interspersed cobble and pebble layer of this unit. This sample has a distribution that leans heavily towards the rounded end of the spectrum, with most of the sediment particles falling into classes 3 and 4, with < 20 particles falling into class 5, and < 10 particles falling into class 2. Given the distribution of sediment particles, this layer can be generally classified as having subrounded-subangular in particle shape. Distribution for sediment particles from this sample can be found in Figure 22C.

The next set of samples come from TU 16, which is the uppermost unit in the Kapana side stream irrigation system. All layers from this unit have sediment particle shape distributions that are like the SBC sample. Layer I has a distribution of sediment particles that fall within classes 2, 3, and 4. Over 50% of the sediments particles for this sample fall into class 4, allowing for this layer to be generally classified as having a subrounded particle shape. The sample from Layer II has a distribution that is nearly identical to that of Layer I, with sediment particles falling into classes 2, 3, and 4. As with Layer I, over 50% of sediment particles fall into class 4, allowing this layer to be generally classified as having a subrounded particle shape. Layer III has a distribution of sediment particles that is like other samples from this unit, with particles falling into classes 2, 3, and 4. Nearly all sediment particles fall into classes 3 or 4, with < 10 particles falling into class 2. Based on this distribution, sediment from Layer III can be generally classified as subrounded-subangular in shape.

The final two samples that are comparable to the SBC sample come from Layers I and III of TU 17. TU 17 was placed in one of the uppermost units in the Kapana side stream irrigation system. The Layer I sample has a distribution that is most like the SBC sample, with most sediment particles falling into classes 3 and 4. The remaining sediment particles fall into classes 2 and 5, with < 10 particles falling into class 5 and < 5 particles falling into class 2. Given this distribution, Layer I can generally be classified as subrounded-rounded in sediment particle shape. The final sample comes from Layer III of TU 17. This sample has a particle angularity distribution that leans towards the rounded end of the spectrum. Most particles from this sample fall into classes 3 and 4, with < 10 sediment particles falling into class 5. Based on this distribution, this sediment sample can be classified as subrounded-rounded in sediment particle shape.

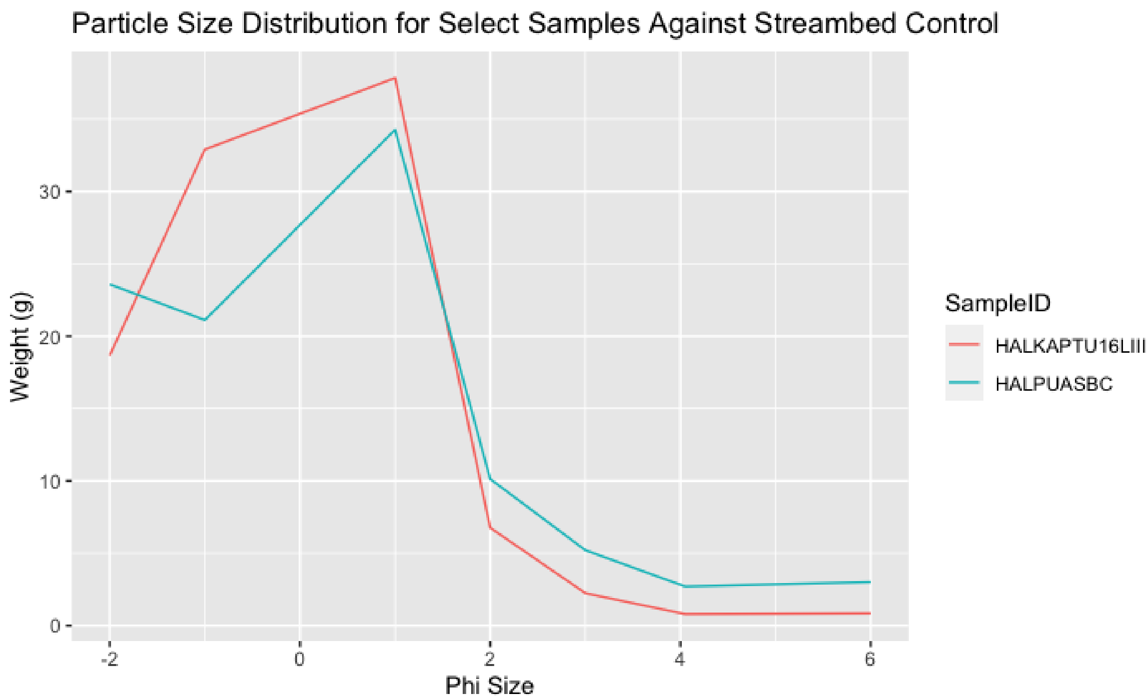

Figure 23. Particle size distribution for selected samples against the stream bed control (SBC) sample. Phi size on x-axis, weight(g) on y-axis.

The final granulometry sample displayed a particle size distribution most like the SBC sample also came from TU-16. This is the uppermost unit in the side-stream irrigation system located in Kapana. The unit was placed on the upslope side of the uppermost intact terrace wall. Two samples from this unit displayed sediment particle size distribution like the DSC, so it is interesting that a third sample also reflected distribution similarities to the SBC sample.

Layer III of TU-16 was loamy and clay-like in texture as with Layer II but has an increased amount of subangular and subrounded rock inclusions. The sediment became more mottled and angular in shape towards the bottom of this unit, although subsoil was not reached. The granulometry sample from Layer III has a similar distribution of sediment particles < 2mm in size. Although the SBC sample has higher levels of particles of phi class -1 (2mm – 4mm), the remaining values for all other class sizes have comparable trends. This similar distribution might be due to previous fluvial deposits or because these terraces were used for diverting water into lower terraces within this system. The distribution might also be similar due to colluvial deposition of more angular sediment clasts, so determining the type of depositional movement might greatly depend on sediment texture and angularity.

Distribution of sediment particle size for the examined samples can be found in Fig. 23.

Discussion of Individual Test Units

To determine whether the sediments in specific areas were fluvially transported, particle size distribution for all units needed to be looked at across space and at different depths, which can provide some insight into how landscapes have been modified throughout time.

Test Unit 10

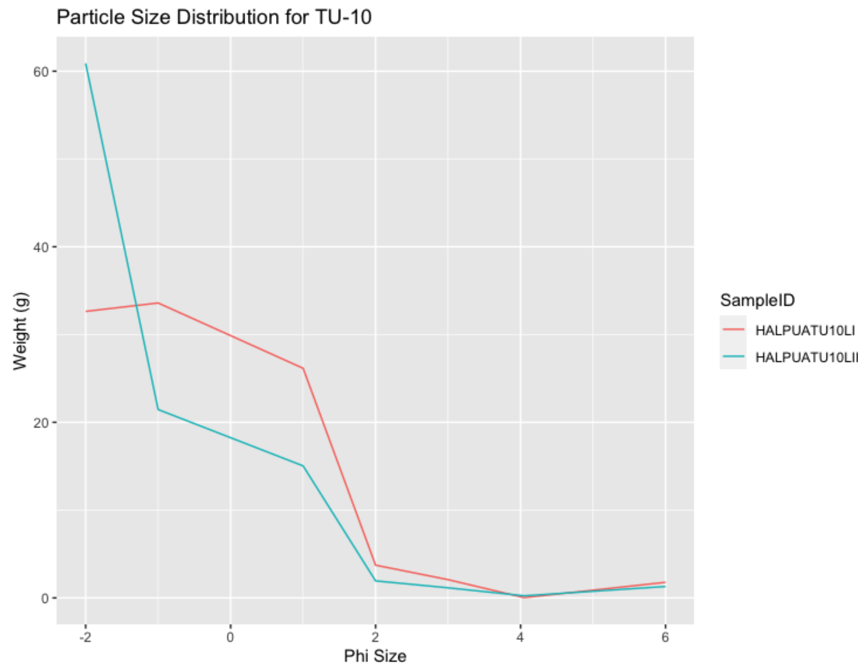

Figure 24. Particle size distribution for sediment samples collected from TU10. Phi size on x-axis, weight(g) on y-axis.

Two sediment samples were collected from TU 10 for particle size analysis and determination of angularity. The sediment sample from LI has a similar particle size distribution to that of the colluvial slope control sample, with a more even distribution of sediment clasts of various sizes. Sediment clasts from this sample were assigned a sub-rounded to sub-angular particle angularity classification, with most sediment clasts falling into one of the two categories.

The sediment sample from LII has a particle size distribution unlike any of the control samples collected in this area. There is a higher distribution of sediment particles greater than 4mm, with a steep drop in sediment particles > 4mm in size. The particle size distribution from Layer II is like that of other upper layer distributions in Kapana and Pualaulau, which is interesting given that it was not classified as a top layer during our test unit excavations. This might suggest that there was a more recent depositional event, most likely a colluvial slope deposit, that more accurately reflects a natural environment as opposed to a completely culturally modified landscape. This might also suggest that our LII is more comparable to the upper layers of other test units throughout this study. Sediment clasts from LII were also assigned to the sub-rounded or sub-angular grades, with nearly and identical distribution to LI. This difference in particle size distribution suggests that there might have been a significant change in functionality in the environment between Layers I and II or a more recent natural depositional event. Angularity classification also suggest natural erosion either from low-flow fluvial or colluvial means.

Distributions of each layer for TU 10 can be found in Figure 24.

Test Unit 11

Two sediment samples were collected from TU 11 for particle size analysis and determination of angularity. The sediment sample from LI has a similar distribution to that of TU 10, LII, which demonstrates a higher presence of larger grained sediment (> 4mm) and lower amounts of fine grain sediment. While this distribution does not match other upper layer distributions for this study site, it does match other particle size distributions from other layers in other test units. Sediment clasts from LI were assigned a sub-angular classification, which slightly differs from that of TU 10. Particle size distribution and angularity classification for LI do not match any of the other controls samples, suggesting that there must have been some cultural modification and use of the area more like dry terraced agricultural as opposed to potential seasonal irrigation.

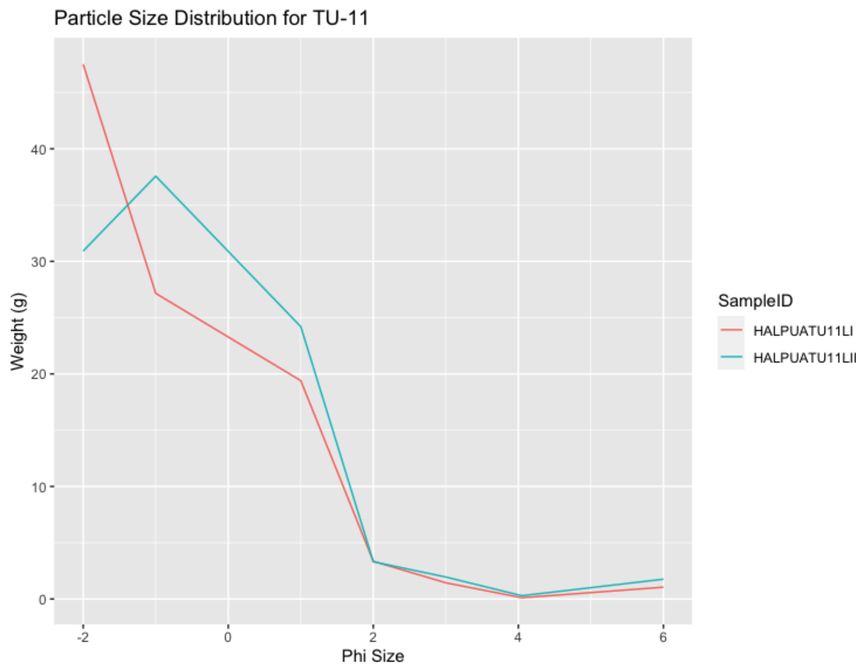

Figure 25. Particle size distribution for sediment samples collected from TU11. Phi size on x-axis, weight(g) on y-axis.

Other upper layers in both Kapana and Pualaulau demonstrate some similarities to the CSC sample, which represent non-irrigated colluvial slope agriculture and other natural depositional events.

The particle size distribution for Layer II is like that of our DSC sample, with a smaller number of large particles (> 4mm), a large amount of sediment in the class size 2mm – 4mm, and a relatively even distribution of the finer grain sediments. The distribution suggests that LII might have been seasonally irrigated or used to direct water transport at some point in time. However, particles from this sample were assigned a sub-angular classification, meaning sediment transport for this layer might have been through non-fluvial deposition. This area might not have been directly irrigated but it demonstrates enough similarity in distribution to suggest some sediment deposition via hydraulic transport. As an entire unit, the distribution of sediment in each layer suggests that water transport might have been common during earlier periods of utilization (LII), followed by periods of non-hydraulic deposition of sediment, use of the area for dryland terracing purposes, or potential abandonment. Distributions of each layer for TU 11 can be found in Figure 25.

Test Unit 12

Three sediment samples were collected from TU 12 for particle size analysis. The samples from Layer I and Layer II have a sediment distribution most like the CSC samples, with higher amounts of sediments from the class sizes 2mm – 4mm and 0.5mm – 2mm. Sediment clasts from LI and LII were assigned a sub-angular classification, suggesting that this terrace was built on colluvial slope parent material.

LIII has a distribution that is somewhat like that of the CSC but has higher amounts of large grain sediment (>4mm) than any other samples in this test unit. Particle clasts from LIII were assigned an angular classification, which is consistent with the idea that these terraces were constructed out of natural colluvial deposits.

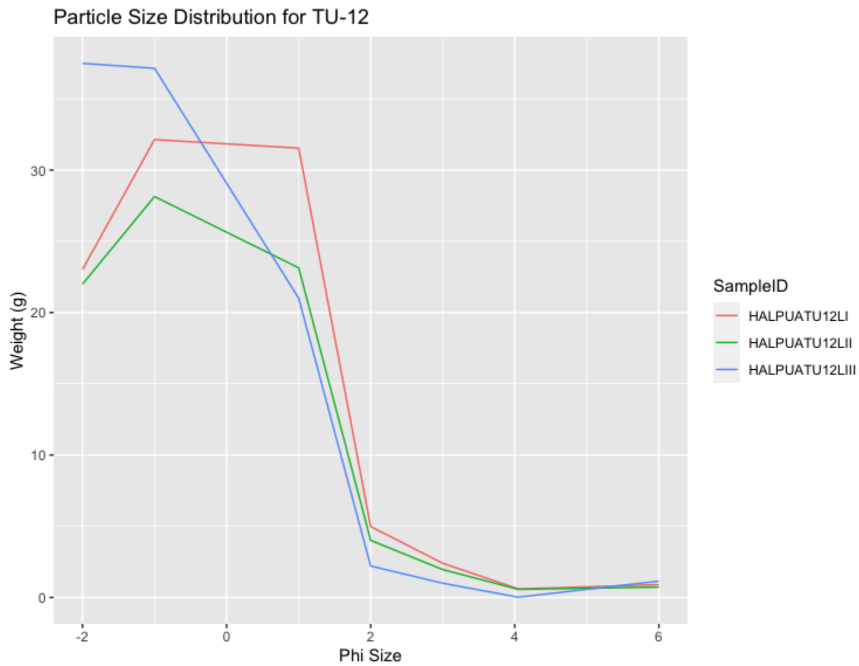

Figure 26. Particle size distribution for sediment samples collected from TU12. Phi size on x-axis, weight(g) on y-axis.

Distributions of each layer for TU 12 can be found in Figure 26.

Test Unit 13

Three sediment samples were collected from TU 13 for particle size analysis. Layer I has a similar distribution to that of the natural or undisturbed sediments of TU 10 and 11, with high amounts of larger grain sediments and lower amounts of fine grained sediments. Sediment particles from this sample were assigned a sub-angular classification, like the other two samples from TU 10 and TU 11 that also had this particle size distribution.

Layer II has a particle size distribution like that of the UIC sample, with low amounts of sediment particles >4mm in size, and high amounts of sediment particles in the class sizes 2mm – 4mm and 2mm – 0.5 mm. There is then an immediate decline in finer grained sediments and particles from this sample were assigned a sub-angular classification. Layer III has a particle size distribution like that of the DSC sample, with a moderate amount of sediment particles in the class size > 4mm, a high amount of sediment particles for class size 2mm – 4mm, and overall higher amounts of fine grain sediments. Sediment from this sample were assigned a sub-angular to sub-rounded classification, suggesting fluvial transport of the sediments.

As a unit, TU 13 expresses several different particle size distribution patterns that are consistent with low-energy fluvial deposition during various phases of terrace use. The particle size distributions for Layers II and III combined with the sub-angular to sub-rounded angularity grade, suggest that hydraulic movement could have occurred at this terrace, either due to seasonal irrigation of the terrace or to water transport for other downslope irrigated terraces. Layer II has higher levels of sediment particles of the class size 2mm – 0.5mm compared to that of Layer III.

Layer III has a higher distribution of sediment for particle class size 2mm – 4mm and a lower amount of sediment particles in class size 2mm – 0.5mm when compared to Layer II, suggesting a change in the potential flow of water during this period of use occupation. Given that the particle size distribution of Layer II and Layer III reflect those seen in the fluvial control samples, it is most likely that the differences observed in Layer I represent a recent or sudden deposition of colluvial sediment.

Distributions of each layer for TU 13 can be found in Figure 27.

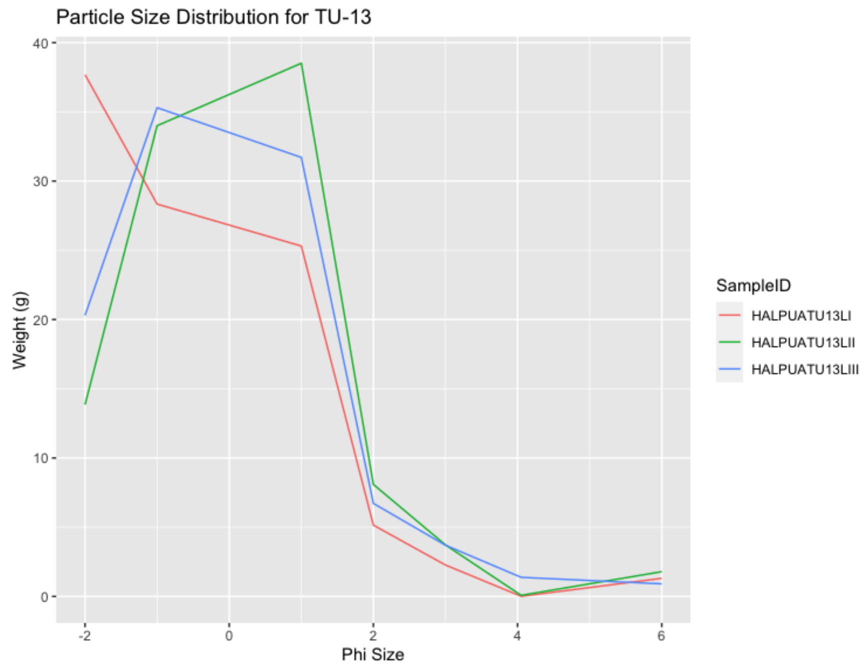

Figure 27. Particle size distribution for sediment samples collected from TU13. Phi size on x-axis, weight(g) on y-axis.

Test Unit 14

Four sediment samples were collected from TU 14 in Pualaulau for particle size analysis. Layer I had a sediment particle size distribution that is not like any of the control samples but does more closely represent distributions for top layers of sediment in TU 10, 11, and 13. The sample from LI has higher amounts of large, grained sediment sizes and a steadily decreasing amount of fine-grained sediments. Sediment particles from this sample were assigned a sub-angular classification, like the other samples that also have this distribution.

Layer II has a distribution like that of the DSC sample, with lower amounts of sediments particles > 4mm in size, but a higher amount of sediment particles of the class size 2mm – 4mm in size. Layer II also has higher amounts of fine-grained sediment particles compared to the other three samples from this unit. Sediment particles from LII were assigned a sub-rounded classification, which is fitting given that its distribution resembles that of the inlet samples. Layer IIB is a sublayer consisting of large subangular and subrounded cobbles and pebbles within the matrix of Layer II. A sediment sample was taken from this sublayer to see if there was any difference in distribution. Layer IIB has the highest amount of sediment particles

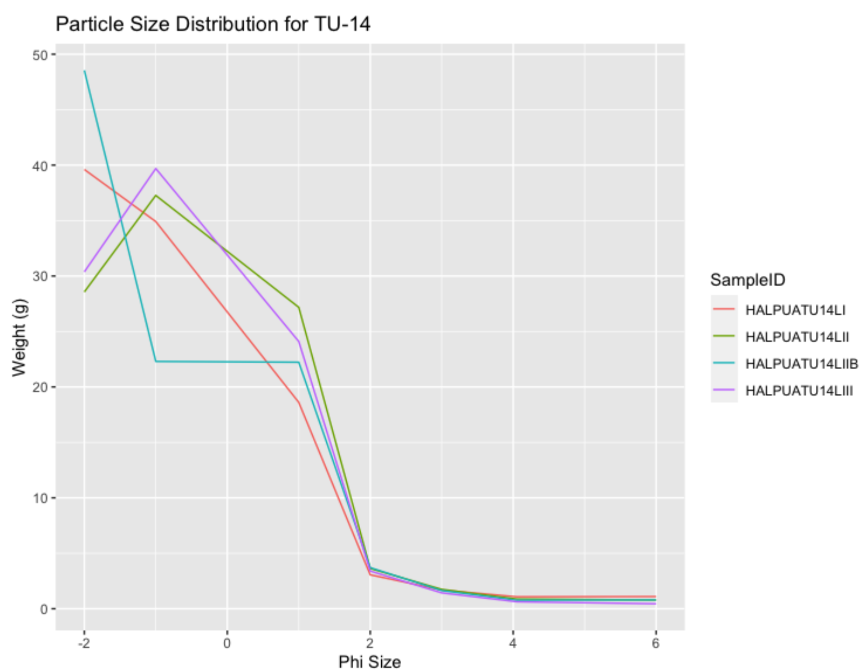

Figure 28. Particle size distribution for sediment samples collected from TU14. Phi size on x-axis, weight(g) on y-axis.

in the class size > 4mm from all samples collected in this study, indicative of a relatively high energy in-wash event. There is an abrupt decline in all other sediment particle sizes in this layer, with the lowest number of fine-grained sediments for this unit. The large amount of sediment particles > 4mm in this specific area of TU 14 suggests that there was a rapid deposition of sediment, most likely via hydraulic movement given the subrounded or waterworn appearance of particles in this sublayer. Sediment clasts from this sample were assigned a sub-rounded classification, which supports the idea of a higher-energy hydraulic event that transported larger cobbles and fine-grained sediment. Layer III has a particle size distribution like the DSC sample and the Layer II sample, with high amounts of sediment particles in the class size 2mm – 4mm and relatively high amounts of fine grain sediment particles. Sediment from this sample was assigned a sub-angular classification, which supports an interpretation of fluvial deposition.

As an entire unit, the changes in particle size distribution over time suggest that the terrace this unit was placed in was constructed via fluvially transported material. Layer III, representing the earliest potential period of use, suggests that there was hydraulic transport of sediment into the terrace. The presence of large, subangular and subrounded pebbles in Layer IIB suggest that there was a rapid, high-energy deposition of sediment, most likely via hydraulic movement given the roundedness of particles in this deposit. This rapid deposition of rounded sediment particles could represent purposeful hydraulic engineering by making use of a flooding event in the adjacent Pualaulau Stream to transport stream sediment into the terrace. Layer II had a similar distribution to that of Layer III and the DSC sample, further supporting our interpretation that this terrace was constructed of fluvially transported material or by a fluvial deposition event. Layer I has a similar sediment particle size distribution to other upper layers in this study, which most likely represent a period of abandonment or minimal use rather than non-irrigated agricultural use that we observe in the distribution of the CSC sample. The change in distribution throughout this unit suggests that there was a period of utilization that relied on either seasonally irrigated or low flow irrigation in this terrace system, with water diverted from the adjacent Pualaulau Stream.

Distributions of each layer for TU 14 can be found in Figure 28.

Test Unit 16

Three sediment samples were collected for particle size analysis from TU 16 in Kapana. Layer I and Layer II have particle size distributions that are most like the UIC sample, with lower amounts of particles in the class size > 4mm and high amounts of particles of the class 2mm – 4mm. Additionally, samples from Layer I and Layer II have similar distributions for fine grained sediments. Layer III has a sediment particle size distribution that is like the DSC sample, with higher amounts of sediment in the class size 0.5mm – 2mm, as opposed to the UIC sample, which has higher values for the 2mm – 4mm class size. All sediment samples collected from this unit were assigned a rounded to sub-rounded angularity classification which further supports the interpretation that the terrace where TU 16 is located was irrigated with water diverted from Maka’ele’ele Stream.

While individual values vary for all three samples, trends in distribution suggest that this entire unit represents multiple periods of fluvial transport or sediment. The sediment particle size distributions from this unit suggest that the terrace TU 16 is in could have been used for seasonal irrigation to divert water throughout its lifetime. The distribution for LIII suggests that there was either more consistent or higher flow rates during the earliest occupation period in this area, followed by lower flow rates or inconsistent seasonal irrigation during L II. The similarities between the LI sample and the DSC sample suggest that the area be subjected to large amounts of hydraulic movement, which is supported by the presence of the permanent Maka'ele'ele stream. Distributions of each layer for TU 16 can be found in Figure 29.

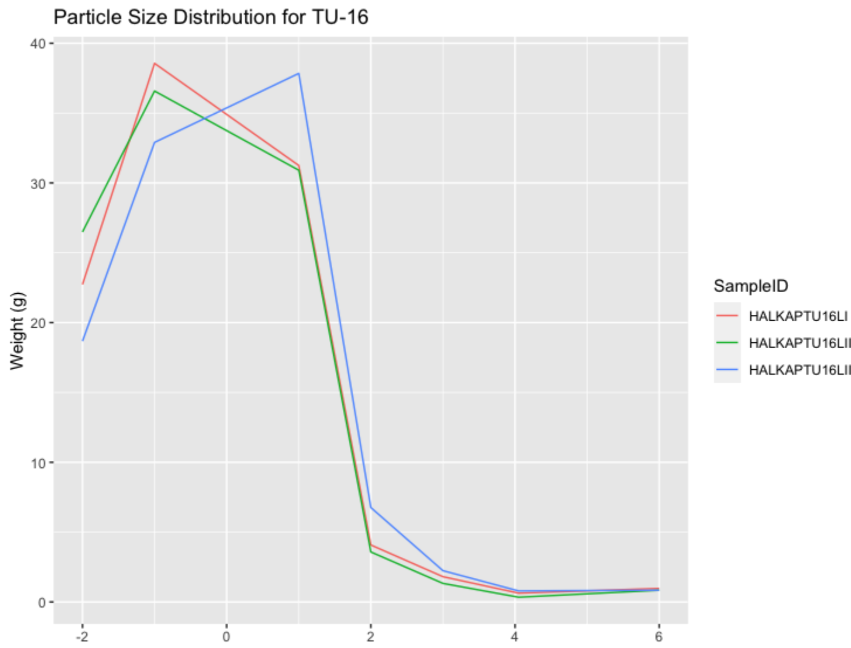

Figure 29. Particle size distribution for sediment samples collected from TU16. Phi size on x-axis, weight(g) on y-axis.

Test Unit 17

Three sediment samples were collected from TU 17 for sediment particle size analysis. Layer I had a sediment particle size distribution that was not like any of the control samples but displayed similar distributions to other sediment samples collected from both study sites. The LI sample had high amounts of sediment particles > 4mm in size, with steadily decreasing amounts of all other particle sizes. Sediment clasts collected from LI were assigned the sub-rounded classification which is consistent with other samples of the same distribution. Layer

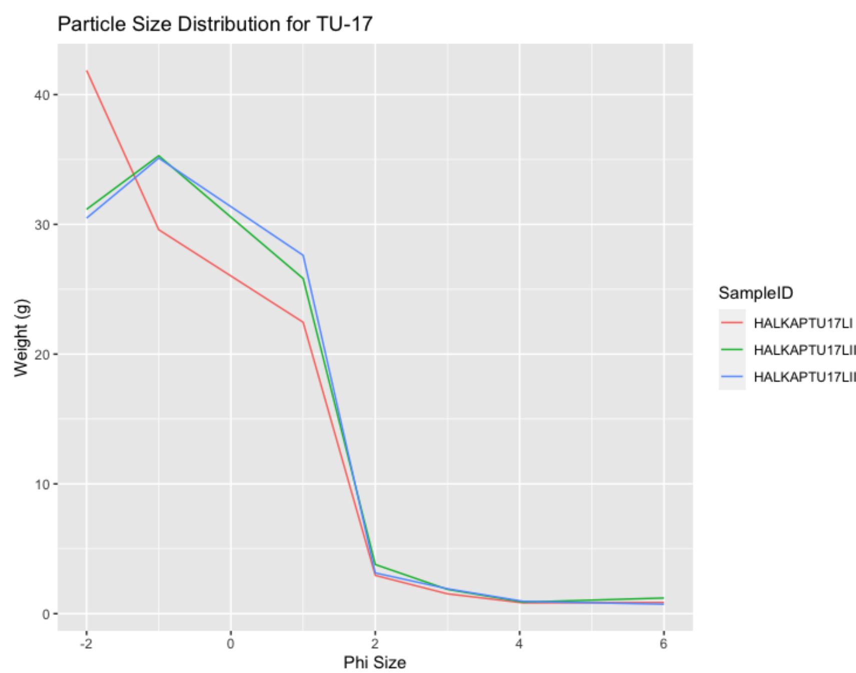

Figure 30. Particle size distribution for sediment samples collected from TU17. Phi size on x-axis, weight(g) on y-axis.

II and Layer III sediment samples had a particle size distribution that was most like the CSC sample, with lower levels of sediments of the class size > 4mm and 0.5mm – 2mm and high levels of particles form the 2mm – 4mm class size. Although this distribution looks somewhat like the DSC sample, the overall trend is more like the CSC sample. However, samples collected from both LII and LIII were assigned the sub-rounded to sub-angular classification, which suggests that some fluvial deposition occurred in LII and LIII.

These sediment distributions suggest that the terrace TU 17 was placed and constructed within a natural colluvial slope, but the angularity of particles in LII and LIII suggest that there might be some seasonal irrigation occurring. Sub-angular and sub-rounded clasts might be caused by natural fluvial erosion given their particle size distribution, but potential irrigation cannot be completely discounted. The LI distribution suggests that the most recent deposits (topsoil) have not been disturbed for a while and potentially represent the most recent period of abandonment.

Distributions of each layer for TU 17 can be found in Figure 30.

Test Unit 20

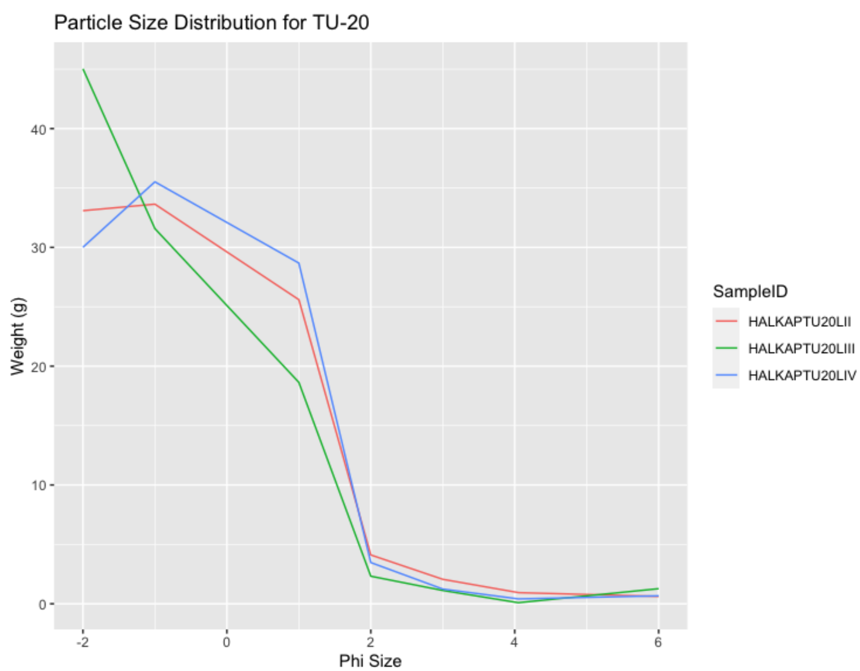

Figure 31. Particle size distribution for sediment samples collected from TU20. Phi size on x-axis, weight(g) on y-axis.

Three sediment samples were taken from TU 20 for sediment particle size analysis. The sediment sample from Layer II has a sediment distribution like the CSC sample, with relatively even amounts of larger grain sediment particles (> 4mm – 0.5 mm). Sediment particles from this sample were assigned an angular classification, supporting the interpretation that the terrace was constructed upon a colluvial slope, and did not involve hydraulic transport of sediment.

Layer III has a sediment particle size distribution with high levels of large sediment grains, with steadily decreasing levels of all other sediment particle sizes. This distribution is different from the control samples taken in the area but is like other samples from this study site. This sediment distribution appears to be unmodified or not used within this agricultural landscape high levels of large grain sediment most likely from a colluvial deposit that was not modified, with low levels of fine grain sediment. One large depositional event is most likely responsible for the sediment in Layer III, followed by a period of abandonment. Layer IV has a sediment particle size distribution like the CSC sample, with high levels of sediment in the class size 2mm – 4mm and lower levels of fine grain sediment. The distribution of Layer IV is like Layer II, which suggests that even during the earliest periods of occupation, the terrace associated with TU 20 did not make use of hydraulic engineering in its construction.

Based on sediment distribution patterns, it is most likely that the terrace associated with TU 20 was originally constructed out of the natural colluvial slope and built up to serve as the final terrace system. These data demonstrate that while this terrace may be in an irrigated system, it was not constructed by hydraulic means. It is more likely that the colluvial sloped was leveled prior to being used in this terrace system. Layer IV most likely reflects the earliest period of modification for colluvial slope agriculture, followed by a clearing or construction event that remained undisturbed or unmodified by fluvial movement, with a final layer of colluvial slope agriculture in the most recent layer. Sediment clasts from LIII and LIV were both assigned the sub-angular classification, supporting the idea that there were multiple depositional events from both fluvial and colluvial means. Distributions for TU 20 can be found in Figure 31.

Discussion

Pualaulau Terrace System (TU 10 – TU 14)

A total of five test units (TU 10 – 14) were placed in a terrace system in the ‘ili of Pualaulau that was hypothesized to have been irrigated by diversion of water from the adjacent tributary stream. Each excavated terrace was selected based on overall condition and location within the system. TU 10 is in the uppermost terrace in the system and had a PSA distribution that didn’t match any of the control samples as well as sub-rounded to rounded clast shapes. Given its location just adjacent to the mouth of a small stream, it is likely that this terrace was used as an inlet to pass water down to lower terraces in the system. A more even distribution in the most recent depositional event is consistent with some fluvial movement, while the high presence of larger particles in LI would support the idea of stream rocks or potential small rock deposit for colluvial and fluvial deposition. TU 11 is in the next lowest terrace and has a PSA and angularity grade that is consistent with TU 10. LI of TU11 has a similar PSA distribution to LII of TU10, both of which did not match any control samples collected. Given that this test unit is also higher up in the terrace system, it makes sense that it would have a similar PSA distribution and angularity classification as the uppermost unit. LII of TU 11 also expressed a PSA that supports fluvial deposition of sediment consistent with hydraulic transport of sediment. TU 12 is in the middle of this terrace system and converges with several other smaller terrace systems. LI and LII of TU 12 have a PSA distribution and angularity grade consistent with the colluvial slope control samples, suggesting that this terrace was constructed on the pre-existing colluvial slope, and did not involve hydraulic transport of sediment. However, the PSA for LIII appears like other PSA distributions in this system.

TU 13 is in the lower half of this terrace system and most clearly demonstrates a PSA distribution most consistent with the DSC samples. The distribution of LI also possesses the signature of a ‘hydraulically transported’ PSA distribution, with LII and LIII both expressing a PSA distribution consistent with the upstream and downstream inlet controls. However, the subangular classification would suggest that while there was fluvial deposition, it was at a relatively low energy flow rate being located towards the bottom of the terrace system.

TU 14 was one of the more interesting terraces in this system, with multiple PSA distributions similar to the fluvial transport pattern previously observed in this system. LI and LIIB also expressed the fluvial transport distribution pattern, with LI classified as sub-angular and LIIB classified as sub-rounded. More recent depositional material could account for the sub-angular classification in LI. LII and LIII have PSA distributions like that of the DSC sample and both have sub-rounded to sub-angular clast classification. This suggests that there were multiple periods of fluvial deposition throughout the use life of this terrace.

Overall, the data produced through particle size analysis and determination of angularity supports the interpretation that some form of hydraulic movement was used to transport sediment within the Pualaulau side stream terraces. The samples that reflected sediment characteristics most like the CSC control samples were most like the result of more recent colluvial sediment depositions or reflected that some terraces were constructed out of the original parent material. Samples collected from the uppermost units closest to Pualaulau stream have sediment characteristics that strongly support fluvial movement, which is supported by its location. Samples collected from terraces throughout the main body of the system possess sediment characteristics of both fluvial and colluvial deposition, suggesting that fluvial movement was present but not necessarily the main form of deposition for construction in this area. Sediment data for the lowermost terrace in this system strongly suggests that there was some form of hydraulic engineering in the construction of this terrace, even though it was built upon colluvial parent material.

The consistent presence of this pattern throughout each of the test units in this system could suggest that there were periods of sediment deposition via fluvial movement, followed by periods of abandonment or construction with colluvial material. Charcoal was collected, when possible, for RC and are not included in this study. Further research would include dating each layer and potentially identifying a dating sequence for use of this agricultural system as well as periods of seasonal irrigation. While climate data was not incorporated into this specific study, looking at past climate data could provide insight on rainfall levels during the calibrated time periods and would better support this theory.

Kapana Terrace System (TU 16 – TU 20)

Previous archaeological research has determined that this terrace system was previously irrigated, making the Kapana terrace system a good control for this study (Kirch and Kelly 1975). TU 16 is the first unit in a series of known irrigated agricultural terraces that were previously used for lo‘i agriculture (Kirch and Swift 2021). All three sediment samples from TU 16 demonstrate PSA distributions to one of the two inlet control samples. LI and LII have PSA distributions that are most like the upper inlet control samples, with low amounts of clasts >4mm, more particles in the size range 2mm – 4mm, with a relatively even distribution of more fine-grained sediment. Sediment samples from each layer have also been classified as sub-rounded, which further supports that this terrace was part of an irrigated system, with some fluvial transport of sediment.

TU 17 is located on the downslope side of the uppermost intact terrace wall and is a mirror image of TU 16. This was another one of the more interesting terraces, with three distinct layers which most likely correspond to three different periods of use. TU 17 expressed the PSA distribution characterized as the ‘hydraulically transported pattern detected in the Pualaulau samples. These sediment distributions suggest that while terrace TU 17 is in a known irrigated system, this terrace might not have been essential or central to this system. The sub-angularity of sediment clasts in LII and LIII suggest that the terrace was constructed primarily from pre-existing colluvium making up the substrate here. Sub-angular and sub-rounded clasts might be caused by natural colluvial slope erosion of from this terrace serving as a catchall towards the bottom of the system.

TU 20 was the lowest and largest terrace in this side stream irrigated system. PSA distributions from this unit show alternating uses for this terrace, beginning with a phase of habitation in the natural colluvial slope, which was later leveled, built up, and used as an agricultural terrace without any significant fluvial deposits. LII has a PSA distribution similar the colluvial slope control, followed by LIII which has the ‘seasonally irrigated’ pattern found in other units. LIV has a PSA distribution that also reflects the colluvial slope control data, suggesting that an earlier period of either dryland terracing or abandonment. Sediment clasts from LII and LIV were classified as angular, while clasts from LIII were classified as sub-angular which support the idea of alternating periods of irrigation and dryland use of this terrace.

Conclusions

Based on data analysis of sediment samples collected from both the Pualaulau and Kapana terraced agricultural systems, it is highly probable that the terrace system in Pualaulau was irrigated through the diversion of water from the adjacent Pualaulau Stream. Moreover, it is evident that at least some of the lower terraces were constructed by using diverted stream flow to hydraulically transport stream sediment to fill the terraces behind their retaining walls. This is particularly evident with the T14 terrace. Geoarchaeological analysis of sediment samples from the Pualaulau terrace system and Kapana irrigated system demonstrate particle size distribution and angularity classification consistent with fluvial deposition of sediment during certain periods of use. These potentially irrigated contexts are characterized by rounded, sub-rounded, and sub-angular sediment clasts, when combined with a distribution that favors fine grained sediment. There was a unique pattern of particle size distribution that was seen in all the terrace samples, which consisted of a large amount of sediment particles >4mm followed by an even distribution of fine-grained sediment. Particles from these distributions were also assigned the sun-rounded to sub-angular classification, suggesting that the corresponding contexts in each unit might represent the same irrigation period.

Whether the Pualaulau and Kapana side-stream terrace systems were permanently or intermittently irrigated cannot be determined on the available data. Maka’ele’ele Stream in Kapana runs year-round, and thus would have had sufficient flow for permanent irrigation of the adjacent terrace system. Pualaulau Stream today runs only after heavy rains. However, in 1969-70 Pualaulau Stream was observed to run even in the dry summer months, although its flow was sometimes just a trickle. It is possible that the Pualaulau Stream’s discharge was not sufficient to irrigate all of the terraces in the adjacent system all of the time.

Utilizing established agricultural systems, like the side-stream terrace systems of Pualaulau and Kapana, for permanent or seasonally irrigated agriculture demonstrates the adaptability of early Kanaka Maoli working and living in Hālawa Valley. As populations continued to grow it was necessary for these populations to adapt to seasonal changes in natural resources, to better support their communities.

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