Weight Sets: Identification and Analysis

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Standardized weights and measures play an important role in the economies of complex societies. Traditionally, archaeometrologists have employed individual weights as their basic units of analysis and, as a result, they have been able to address a limited range of questions concerning the economic role of weights. I propose a shift in emphasis from individual weights to sets of weights as the primary units of analysis. Using cases from the Aegean Bronze Age, I present a method for reconstructing sets of weights, offer criteria for their analysis and discuss the implications of this new perspective.

Introduction

In this article I propose a new way of looking at weights found in archaeological contexts: one that emphasizes weight *sets* as opposed to *individual* weights. Traditionally, archaeologists have treated individual weights or full assemblages as their primary units of analysis. With this approach, they have been able to identify base units of measurement and assign weights to various cultural systems (e.g. Minoan mina, Mesopotamian shekel). Consequently, they could infer points of contact between distant peoples. While progress continues to be made along these lines of research (see papers in Alberti *et al.* 2006 and Foster & Laffineur 2003), there are limits to the kinds of questions that can be addressed by structuring the data in this way. Shifting the focus of investigation from individual weights to sets of weights enhances our understanding of ancient metrology. While the concept of the set has been applied to weights before (e.g. Kroll 2008, 43–4; Petruso 1981; Pulak 1996), archaeologists have yet to establish any explicit methodology to reconstruct sets or to assess their intrinsic characteristics.

This article has two primary goals. The first is to present a method by which archaeologists can reconstruct sets of weights. To do this, I consider raw material, form and find-spot in a more explicit framework than have previous analysts. I consider these variables in light of established metrological principles to identify coherent sets of weights. The second goal is to suggest criteria by which reconstructed sets can be assessed. Sets of weights have certain measureable qualities that can help scholars infer what could have been weighed and how accurately. I outline seven such features: capacity, range, accuracy, incrementation, standardization, conformity and archaeological context.

These characteristics form the basis of my subsequent analysis of sets of weights from the Vapheio tholos tomb, the Cape Gelidonya shipwreck and the Bronze Age site of Malthi-*Dorion* (hereafter Malthi) in Greece (Fig. 1). The three case studies were chosen because they progress from the straightforward case of a complete set of weights found in a discrete context to the less secure case of weight sets that appear to have been fragmented and subsequently reconstituted in different combinations over the course of a few centuries. I begin with the case of the Vapheio tholos weight set because it is unambiguous—the analytical method outlined below is easy to apply there. The examples of the Gelidonya shipwreck and the long-occupied site of Malthi are progressively more complicated. The method presented here, I propose, can help us make greater sense of the use of weights deposited at these sites and, by extension, elsewhere as well.

Background

Of necessity, most of the research on weights and measures in Aegean archaeology has treated them as the ends of study. Before archaeologists could begin to consider the role of measurement in Aegean society, some basic facts had to be established. The standard

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Figure 1. *Map of main sites discussed in the text. 1. Malthi; 2. Vapheio; 3. Ayia Irini; 4. Akrotiri; 5. Mochlos; 6. Troy; 7. Cape Gelidonya; 8. Tarsus; 9. Ugarit.*

approach, to date, has focused on three fundamental questions. The first, naturally, is identifying the artefacts used in measuring. The second is figuring out the values of the units (in terms of today's cognate metric system) and establishing how the Aegean systems relate to contemporary metrological systems from elsewhere in the Mediterranean. A third priority has been to reconcile the metrological system documented in texts with those reflected by the artefacts. None of these are straightforward tasks. Artefacts related to measurement are difficult to recognize. The base units of mass, such as the mina or shekel, are in fact not very standardized when they appear in material form, and usually their values are determined by a 'best fit' rather than an exact correlation. Finally, while the texts provide a good deal of information about aspects such as nomenclature, how units are subdivided, and what is being weighed, they rarely provide a direct link to the physical artefacts related to weighing that are recovered by archaeologists.

One advantage archaeologists have in studying weights in the Aegean and eastern Mediterranean is that they often recover the physical prototypes of the standard. In a few cases, weights are marked or shaped in characteristic ways, making them easy to identify. For example, Aegean lead weights are almost all discoid in shape and could serve little other purpose. Other times, weights can consist of stones that are recognizably, if only minimally, worked. They may be flattened on one side, or marked with notches, confirming their status as weights. Such markings usually indicate their relative value (Michailidou 2006; Petruso 1992). In some cases, context helps archaeologists identify objects as weights and make inferences about their function (Bobokhyan 2008; Michailidou 2010). When found in useful sets or in conjunction with other weights, ambiguous specimens may be identified with greater confidence.

In the majority of cases, however, the identification of weights is difficult. Often weights cannot be differentiated from objects not used for weighing. For example, Valmin (1938, 384) observed a modern-day Messenian chandler using pebbles to supplement an incomplete set of weights. We can imagine such instances occurring in the past. As a result, archaeologists risk mistakenly leaving out objects used as weights in their studies (Valmin 1936–7, 7–8). Similarly, non-weights, perhaps because no other

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explanation can be put forward for their function, might erroneously be included in catalogues of weights. Valmin, in his study of weights from Malthi, included seven terracotta spheres in his catalogue (1938, 380–82). Petruso correctly discounts these specimens (1978, 135), explaining why terracotta is not a desirable material for weights (1978, 5).

Furthermore, as material artefacts, weights endure differential preservation and their masses upon discovery may not reflect their original ones. Metal weights oxidize and flake over time while stone weights can be chipped. Even when weights are found relatively intact, there is a good deal of variation in how closely they achieve their target masses. Given this variability, and the possible alteration of a weight's physical attributes over time, solitary weights are usually of limited use to archaeologists.

Despite the difficulties noted above, the quality of research on the subject of Aegean and eastern Mediterranean weights is impressive. Often unrecognized and/or uncatalogued in the past, weights are now regularly given full treatment in excavation reports (e.g. Alberti & Aravantinos 2006; Aravantinos 1995; Petruso 1992; Rahmstorf 2008). When a site yields sufficient specimens, certain types of analyses become possible. Statistical techniques, such as quantal analysis (Cherry 1981; 1983; Kendall 1974; Pakkanen 2011; Petruso 1978; 1992; 2003; Pulak 1996; 2000) have been applied to reconcile the variability in the masses of weights with their 'best fit' and researchers can usually assign weights to the metrological standards to which they conformed. The concept of the normzone, pioneered by Viedebantt (1923), also figures prominently in archaeometrological analyses. The normzone, designated as a percentage, delimits the range around an ideal value that is represented by actual examples of weights. This gives us an idea of the margin of error that was tolerable in a weighing system. These metrics, now commonly recorded, have been applied by archaeologists to weights at most sites in the Aegean and beyond, thereby enabling some attempts at comparative analysis. Most notably, roughly a third of Petruso's (1992) publication of the weights from Ayia Irini on Kea is devoted to documenting comparanda from elsewhere in Greece. Looking beyond the Aegean, we have a much more thorough understanding of the international context of Aegean weighing systems than ever before (see papers in Alberti *et al.* 2006; Foster & Laffineur 2003; Morley & Renfrew 2010).

The basic unit of weight common to most Bronze Age Mediterranean cultures was the talent, a mass of roughly 28–30 kg. A talent consisted of 60 minas, the masses of which hover around 500 g. The Mycenaean mina weighed approximately 554 g, while the Minoan mina weighed approximately 483 g (Petruso 1978; 1992). There was a good deal of variation in how closely this standard was achieved by actual weights both between sites as well as within single sites during various chronological phases (see Petruso 1992). Likewise, each major sub-region of the Eastern Mediterranean had its own mina (Powell 1971, 198–207, table 8). The Mycenaean system of weights was probably adapted from the Minoan system and then, as Alberti put it, 'transformed, according to local needs and traditions until the late form attested in the Linear B tablets' (Alberti 2006, 316). Those local traditions may have included elements from the Early Helladic system of weights, which had already been reconciled with the Syrian and Mesopotamian systems (Rahmstorf 2003; 2006; 2010). The transition likely began during the Middle Bronze Age, as there are weights found in Middle Helladic levels at Malthi that indicate the use of both the Minoan and the Mycenaean systems (Petruso 1978: Valmin 1938).

Standardization is a process, one that is constrained by technology as well as by cultural attitudes. Technologically speaking, weights are a physical prototype of a predefined mass. They are, for the most part, manufactured objects. A craftsperson's ability to make a weight that accurately conforms to its intended mass (i.e. a weight that is standardized) may be limited by their personal skill as well as the quality of the instrument used to compare the weight to its standard. Moreover, the definition of equivalency, or the determination that the quality of a weight is 'good enough,' can vary for a variety of culturally defined reasons. A scale that is off by five grammes would not be considered acceptable when weighing saffron, but would not elicit an objection if it were used to weigh figs. The degrees to which weights achieve their intended masses, then, are variables that archaeologists can investigate. The Aegean witnesses some variability in both the definition of standards of mass as well as in the crafting of weights that attempt to conform to those standards. For example, as mentioned above, while the standard Minoan mina is estimated to be 483 g, in practice, it can range from 470 g (Phylakopi) to 488 g (Vapheio) (Petruso 1992, 81).

Weights themselves occur in a range of materials. Hard stone, in particular haematite, became the material of choice throughout the eastern Mediterranean during the Bronze Age and among haematite weights, the sphendonoid, or barrel shape, was prevalent. While present in the Aegean, such weights were not common. There, lead disks were preferred. Limestone was also a common material for weights in both rounded (spheres, hemispheres and cones) and

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cubed shapes. In the former cases, the identification of haematite sphendonoids or lead disks as weights is indisputable. Limestone weights on the other hand, are not as readily identifiable, but we can have confidence in their identification as weights when their contexts (e.g. if found with scales or other weights), or when comparisons of formal properties with known examples, provide positive clues.

From weights to weight sets

One of the goals of this article is to offer a framework to further the study of weights in their broader economic context. In contrast to the rich body of research described above, little work has been conducted on the economic, social and political aspects of measuring—who is doing the measuring, in what context, for what purpose, or how measures relate to the things being measured. Notable exceptions are the work of Hruby (2010), Lang (1964), Michailidou (1999; 2006; 2010) and Pulak (1996). The main reason that previous research has not moved far beyond questions such as 'how many grammes did a mina weigh?' is the way in which the data have been structured. The basic unit of analysis has been the individual weight itself and, to be fair, for good reason. Identifying a baseline unit of measurement in use at a site with confidence requires as many *individual* examples of weights as possible. The higher the sample, the more confident we can be in the results (if they form a pattern). As long as the sample contains actual weights that conform to the weighing system to which they are assigned (Minoan, Mycenaean, Egyptian etc.), then complete or coherent sets need not be present. However, demonstrating the existence of measurement systems and documenting the absolute values of the units that comprise those systems tell us little about the broader economic institutions that prompted their adoption.

Reconstructing sets of weights

The first step in this new approach is to reconstruct coherent sets of weights, that is, sets that can be used to measure a range of masses at regular intervals with no gaps. We must begin by considering formal attributes such as material, form and proximity to other weights. Weights that are made of the same material are more likely to be part of the same set and possibly adhere to the same standard. This factor is less important in sets used privately than those used publicly (more on the performance of weighing below). As for form, weights of the same shape are more likely to be part of the same set and adhere to the same standard. Again, this factor is less important in sets used privately than those used publicly. Finally, in terms of proximity, weights that are found together are more likely to be part of the same set and adhere to the same standard. Ideally, these three variables will overlap: weights of the same material and shape found together can confidently be interpreted as belonging to same set. The case of the weights found in the Vapheio tholos tomb discussed below is one such example, as there is little dispute in identifying this set. The case study that follows, consisting of weights from the Cape Gelidonya shipwreck, is slightly problematic. However, considering the criteria of material, form, and proximity, at least one set of weights from the wreck can be reconstructed with a high degree of confidence.

Most ancient cases, alas, are not that straightforward. In addition to the slew of post-depositional processes that can affect the integrity of any archaeological context (Schiffer 2002), sets of weights are highly fragmentable. Individual weights can be removed from sets (or lost). The sets may lose their utility as a result. In other cases, a set can be reconstituted by replacing a lost weight with another one of the same mass, even if the replacement is different in material or form. Indeed, entirely new sets can be created in this fashion. Such actions, however, have consequences. They may adversely affect the performativity of a set of weights—uniformity elicits trust, after all. They may also adversely affect the recognition of the set by archaeologists. These considerations lie at the root of my choice of Malthi as a third case study. The weight sets at that site endured these sorts of transformations and without an explicit method, their reconstruction would not be possible at all.

With these considerations in mind, I present here a method to identify and analyse potential sets of weights found in archaeological deposits. The method has two parts. In the first phase, I reconstruct sets of weights. In the second phase, I analyse the properties of the sets. The method is recursive. That is, we can also examine a reconstructed set's properties in order to assess our confidence in the reconstruction. To reconstitute possible sets of weights, I take the following steps. First, I isolate one or more of the variables—material, shape, or proximity—and group weights according to these criteria. Second, I determine the system of measurement to which the weights conform. Here I follow the analyses already performed by Petruso (1978; 1992), with some slight modification when necessary. I then determine the equivalent fraction or multiple of the base unit of each weight. Again, this calculation follows the method outlined by Petruso (1978; 1992).

Once the system behind the weights is established, I reconstruct the set based on its conformity

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to that system. To be a valid set, it must be coherent. A set with weights consisting of x, 2x, 3x, 12x, 15x, 64x, 128x has gaps (between 6x and 12x, 70x and 76x, etc.) and is of limited utility compared to one of x, 2x, 4x, 8x, 16x, 32x, 64x, and 128x which can measure the mass of any object from x to 255x with a precision of one x-unit. If an incoherent set may be made coherent by the addition of a weight of a certain value that is not present, it may be possible to conjecture that the weight existed but is missing. One could reconstruct such sets as well, albeit with slightly less confidence. In the case studies presented in this article, however, I only consider sets that are coherent with the weights that are present.

Each weight is treated as having the same value throughout its use in the set, even if inaccuracies in its mass (of which there are many examples) produce errors that could be corrected by using alternative combinations. For example, say a weight designated as three units and one designated as five units have masses that are slightly below their ideal value and combining them produces a weight that is closer to seven units than eight. It would be tempting to add a one-unit weight to correct this inaccuracy. This procedure, however, would invalidate the set, or at least overcomplicate its use, since in some instances the three-unit weight would count as three units and in others it would not. For the sake of consistency, therefore, each set is defined by its internal logic, not its accuracy. Accuracy, by which I mean how closely each interval reflects its target value, is a quality that this study aims to ascertain.

In a similar vein, I look for repeatable patterns rather than maximum accuracy in determining which combination of weights form each interval in cases where multiple combinations of weights can achieve them (Petruso 1992, 9) (see the discussion of the Vapheio weights below). I have found that using this principle makes sense because certain incremental patterns repeat themselves, suggesting a mnemonic device that is easy to follow. Using such a method is particularly important when working with a set of unmarked weights of varying multiples of the base unit.

Once the sets are reconstructed, I assess the following characteristics:

1) Capacity: The capacity of a set informs us about the commodities it could have weighed. Sets composed of light weights, for example 5 g to 50 g, would not have been effective tools to weigh wool, while a 2 kg to 6 kg set would not work well for gold.
2) Range: The set's range consists of the high and low values of what it can measure. Range provides information about the set's versatility and its intended purpose. Measuring daily rations to workers would not require a set with a wide range of values, while collecting tax contributions from dispersed production units of widely varying sizes might.
3) Accuracy: Accuracy is the difference between the actual value for each incremental mass and its ideal value. It indicates the level of tolerance for error in a given measurement context and serves as a fundamental basis for comparison between sets. I consider the range of error among the masses (or combinations of masses) themselves as well as the range of error among the intervals between masses.
4) Incrementation: Incrementation is the spacing in between units of measurement throughout the set's range. It is an indicator of the precision, or the degree of refinement called for in the act of weighing. Often, sets with lower capacities tend to have finer incrementation and are, therefore, more precise. I calculate incrementation using one side of the scale only. That is, I do not include in this analysis the possibility, as cogently suggested by Lang (in Goldman 1956, 267), that weights could be placed on both pans of a scale, effectively creating a third weight whose mass is the difference between the two.
5) Standardization: For the purposes of this study, standardization refers to the formal similarity of the weights in a set to each other. This factor directly relates to the set's performativity. Sets with weights that are identical in material and shape have high performative value compared to sets with mismatched weights, even if their degrees of accuracy are comparable. Other variables that can enhance performativity, such as color or the presence of markings, are not considered here.
6) Conformity: To which weighing system does a set belong? We can have greater confidence in the validity of reconstructions of sets of weights that conform to known metrological systems, such as those recorded in contemporary texts, than in sets that conform to idiosyncratic units. Moreover, the source of the system in use is telling. A set that conforms to a foreign system of measurement may imply trade with that region, whereas a locally derived system may have been used solely for domestic purposes.
7) Archaeological context: For example, the function of the spaces in which weights are found and the artefacts associated with the weights can provide clues concerning their use. Weights found in workshops may have commercial or non-commercial functions (as in weighing ingredients). Weights

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found in central places may be part of redistributive operations. Multiple sets of weights, conforming to different systems, found together may indicate commercial enterprise.

Case I: Vapheio

In some instances, the identification and interpretation of a set of weights is relatively unproblematic. One such case is the set of weights found in the Vapheio tholos tomb. I discuss it first in order to demonstrate my methodology in a clear manner. I then turn to the other case studies, where there is greater variability among the weights and their contexts, and where the considerations above are of greater help in reconstructing possible sets from that site.

The Vapheio tholos tomb dates to around 1500 BCE, during the Late Helladic IIA (LHIIA) ceramic phase. The assemblage of weights discovered there consists of nine lead disks. The weights were found in the unplundered cist underneath the floor of the tomb (Tsountas 1889). Their proximity, form and raw material all indicate a coherent set. The masses of the weights range from 54.4 g (*c.* x) to 985.9 g (*c.* 18x). With a mean unit of *c.* 60.2 g, and factoring in a slight loss of mass due to weathering and oxidation, this set would likely have been used to weigh objects from 60 g (x) to 4.14 kg (69x) in 60 g increments. Judging by the facts that each 60 g increment could be achieved via different combinations of weights, and that the weights were found in a closed deposit, I consider the set to be fully intact. However, two of the weights were damaged and thus underweight. Since the cist was not disturbed, it seems unlikely that the damage would have occurred after they were buried and therefore they were probably buried in their broken state. Both broken pieces have corresponding weights with similar masses among the other pieces of the set. It may be the case, then, that this was originally a set of seven weights, not nine, and the two broken weights were replaced at one point with intact ones. If that did occur, the maximum capacity of the set would have been 3.78 kg, not 4.14 kg. The 60 g incrementation would not have been affected by removing those two extra weights.

The capacity and range of masses that the Vapheio set could have weighed (60 g to 3780 g in 60 g intervals) suggest the weighing of moderately sized commodities such as wool and possibly bronze. In what is likely not a coincidence, the three heaviest weights combine to form a mass of 1 LANA, the unit used to measure wool, as documented in the somewhat later Linear B tablets of Pylos and Knossos. As the tomb is obviously not the place where weighing took place, we can say little about the set's primary context. However, the fact that it appears in a tomb, is a coherent set, and was buried with related paraphernalia including scales and numerous sealstones (artefacts also employed by people involved in commodity exchange) (Tsountas 1889), makes it plausible that the occupant of this tomb actually used the set to weigh things (Kilian-Dirlmeier 1987, 206–7, 209 Abb. 9).

For the purposes of this study, I consider the seven undamaged lead discoid weights and do not include the two damaged ones. The base unit (x), as calculated by Petruso (1992, 57) is 60.2 g. This value is common in weight sets throughout the Aegean world, forming the basis of weight sets at Ayia Irini, Akrotiri and Mochlos, to name just a few sites (Petruso 1992, 34, 41, 44). The masses of the seven weights, their attribution (e.g. how many base units each one represents), the resultant base unit, and relationship to the ideal base unit are listed in Table 1. As is apparent, the first five elements of the set form a geometric sequence with a factor of two, making this set extremely user friendly. Each interval between 1x and 63x can be achieved using a simple combination of weights and the progression from one interval to the next follows an easy-to-remember pattern. For example, the progression from 4x to 8x is 4x, 4x+1x, 4x+2x, 4x+2x+1x, 8x; and the progression from 8x to 12x is 8x, 8x+1x, 8x+2x, 8x+2x+1x, 8x+4x. This system, with repeating combinations of weights to form the intervals between values marked by individual weights, is easy to follow by the person doing the weighing and also easy to interpret by an observer, even one who is not a regular user of the set. In the case of Vapheio, therefore, we have a coherent set of weights that conforms to the Minoan standard.

As for accuracy, no physical set of weights is a perfect manifestation of its ideal system, and determining a set's degree of accuracy is useful in assessing the 'tolerances of accuracy' (Petruso 1992, 6) deemed acceptable by the people who used the weights as well as for the purposes of comparing sets. In the case of the Vapheio lead weights, I admit that this exercise may be somewhat specious, since lead corrodes and the masses of the weights as measured after excavation were likely slightly different than they were during deposition. However, it is worth going forward to continue the outline of the method. I assess the accuracy of the set of weights using a number of metrics. These include the average difference between the resultant unit calculated for each interval and its ideal value, the range and maximum error value, and the normzone, defined above. The normzone is calculated by subtracting the lowest calculated base unit among

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Table 1. *Masses and base units of the lead discoid weights from the Vapheio tholos tomb set.*

Attribution	Mass (g)	Ideal mass (g)	Error (±g)	Base unit (g)	Ideal base unit (g)
1	54.4	60.2	−5.8	54.4	60.2
2	133.3	120.4	+12.9	66.7	60.2
4	236.3	240.8	−4.5	59.1	60.2
8	487.8	481.6	+6.2	60.1	60.2
16	944.3	963.2	−19.9	59.0	60.2
16	953.2	963.2	−10.0	59.6	60.2
16	985.9	963.2	+22.7	61.6	60.2

Table 2. *Comparative table of weight sets discussed in the text.*

Set name	Base unit (g)	Normzone	Range (g)	Average increment (g)	Average error as a percentage of target mass for each combination of weights	Average increment error as a percentage of ideal increment
Vapheio Tholos	60.2	10.2%	54.4–3795.2	60.3	1.3%	17.3%
Cape Gelidonya	9.4	2.5%	9.3–583.3	9.4	1.0%	7.3%
Malthi Haematite	8.3	5.0%	16.8–390	4.1	1.0%	20.7%
Malthi Rounded	492.2	4.0%	21.0–2155.6	20.5	0.8%	13.0%
Malthi Cubed	547.9	1.5%	363.1–3291.6	22.9	1.2%	16.2%
Malthi Centre	554.3	3.2%	180.4–1818.1	23.4	1.0%	24.0%
Neo-Babylonian Agate Ducks	8.2	2.6%	16.7–91.9	2.0	0.9%	27.4%

the individual weights in a set from the highest, then dividing that difference by twice the mean unit. Here, this is (66.7–54.4)/(2 × 60.2), or 10.2 per cent. In addition, I assess the degree of accuracy among the intervals between units in terms of their range, average error, range of error, and maximum error. This distilled method of assessing a set's accuracy provides a baseline for comparison of different sets of weights that may conform to varying systems, have different ranges, and consist of units of varying magnitude.

At Vapheio, the average margin of error between the actual mass of any combination of weights and their ideal mass is 13.4 g with an error range of 0.5–38.8 g. This amounts to an average error of 1.3 per cent and a worst-case error of 10.7 per cent. Errors in incrementation range from –27.7 to 18.7g with an average increment error of 10.4 g or 17 per cent and a worst-case error of 46 per cent. In roughly 60 per cent of the cases, the incremental error is below 10 per cent. These data provide some useful information on their own and, because they are based on features that are intrinsic to the set, they are especially useful in drawing comparisons with sets of weights found elsewhere (Table 2).

Case II: Cape Gelidonya

The second case study consists of a set of weights from the Cape Gelidonya shipwreck dating to around 1200 BCE (Bass 1967; Pulak 1996). Bass classified 60 objects as weights or possible weights in his initial publication of the shipwreck and Pulak, in his restudy of the material, added six more to the assemblage for a total of 66. Almost all of the weights were clustered together in what is considered to be the ship's cabin (Bass 1967, 135). They were crafted in a variety of shapes (sphendonoid, cylindrical, domed, oblong and sugar-loaf) in both stone (mainly haematite) and bronze.

Here we are concerned with the ship's sphendonoid weights which, when isolated from the rest of the assemblage, form a coherent set. Both Pulak and Bass identify certain weights as sphendonoids, but their classifications do not match up. In my analysis, I consider Pulak's 'typical sphendonoid' group (1996, 204, table 33), which roughly corresponds with Bass's sphendonoids (1967, 135–7, fig. 146) with the exception of a few pieces (W24n, W36n and W63n) that are reclassified as loaf-shaped weights and the addition of one weight (W7n) that was discovered at the site nearly three decades after the initial excavation of the wreck. Both Bass and Pulak exclude one well-crafted sphendonoid (W64n) from the group as it was found in an entirely different context within the ship (Bass 1967, 135; Pulak 1996, 171). To avoid special pleading, I exclude this specimen as well. Counting it would not affect the outcome of my analysis in any material way other than adding *c.* 500 g to the range of the set.

The Gelidonya sphendonoid set, then, consists of eight weights ranging in mass from 9.3g (*c.* x) to

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Table 3. *Masses and base units of the weights in the Cape Gelidonya 'typical sphendonoid' weight set.*

Pulak inventory number	Attribution	Mass (g)	Ideal mass (g)	Error (±g)	Base unit (g)	Ideal base unit (g)
W2n	1	9.3	9.4	–0.1	9.3	9.4
W7n	2	18.1	18.8	–0.7	9.1	9.4
W14n	3	28.0	28.2	–0.2	9.3	9.4
W23n	5	45.3	47.0	–1.7	9.1	9.4
W35n	7	63.4	65.8	–2.4	9.1	9.4
W37n	7	66.6	65.8	+0.8	9.5	9.4
W39n	7	69.0	65.8	+3.2	9.9	9.4
W60n	30	283.6	282.0	+1.6	9.5	9.4

283.6 g (*c.* 30x) (Table 3). The set could have been employed to weigh masses from 9.3 g to 583.3 g (62x) in 9.4 g increments. Given its utility, the set appears to be fully intact as it is, although as noted above, weight W64n (499.5 g) could easily fit into this set with a value of 54x, extending its range to 1082.8 g (116x). The capacity, range and precision of the set suggest the weighing of moderate quantities of metal. Finds of scrap metal on the wreck coupled with Bass's suggestion that at least one of the merchants aboard the ship was a tinker lend further support to this interpretation (1967, 163).

In terms of quality, the set is quite accurate. Following Pulak (1996, 204), I calculate the base unit of the set to be 9.4 g. The normzone is a narrow 2.5 per cent. The average margin of error between the actual mass of any combination of weights and their ideal mass is 2.9 g with an error range of 0.0–6.8g. This amounts to an average error of 1 per cent and a worst-case error of 3 per cent. Errors in incrementation range from –1.4 g to 5.0 g with an average increment error of 0.7 g or 7.3 per cent and a worst-case error of 53 per cent. In roughly 80 per cent of the cases, the incremental error is below 6.3 per cent.

In addition to these impressive technical characteristics, the relative uniformity of shape and material of the weights in this set lend it high performative value. Sphendonoid haematite weight sets were known throughout the eastern Mediterranean, with weights of this type recovered at Thebes (Alberti & Aravantinos 2006), Lefkandi (Kroll 2008; Popham & Lemos 1996), Poliochni (Bernabò-Brea 1964), Troy (Bobokhyan 2006), numerous sites on Cyprus (Petruso 1984), the Uluburun shipwreck (Pulak 1996) and Ugarit (Bordreuil 2006), to name but a few. Thus sets such as this one would have been familiar to most people involved in long-distance commerce. Similarly, the set's conformity to a well-known standard, in this case either the Ugaritic shekel or the Egyptian qedet of 9.4 g (Pulak 1996), would further enhance its authenticity. The merchants on board this far-roaming commercial vessel who possessed this set of weights most likely conducted much of their exchange with strangers. In such situations, trust is more tenuous than when exchange partners are familiar with each other. A highly standardized set of weights using a known standard such as this one would help establish the legitimacy of the transactions in which it was used.

Reconstructing and analysing the Gelidonya sphendonoid set is not as straightforward a task as that for the set of weights found in the Vapheio tholos tomb. The weights that constitute this set were recovered from a mixed context that included weights from other sets. Nevertheless, using the guidelines identified above, it was possible to cull a coherent set from the larger assemblage, and we can be confident in the reconstruction. One factor that should further boost confidence is the synchronic nature of the deposit. Time is a variable that we can exclude in this case, since we know that all of the weights on the ship were carried and deposited at the same time. In the following section, I turn to a more complicated case, in which space, time, and standardization are more varied.

Case III: Malthi

Let us now turn to the site of Malthi, a Middle Helladic–Late Helladic III (MH–LHIII) settlement in Messenia, where the situation is far more complicated. Valmin (1938, 25, 221) concluded that occupation of the site spanned the entire Bronze Age. Subsequent analyses of the site's pottery suggest that full-scale habitation there more likely began well into the MH period (Hope Simpson & Dickinson 1979, 174; Howell 1992, 73; McDonald *et al.* 1992, 759; but see Blitzer 1991, 6–7 for sporadic earlier material at the site). Despite lingering questions concerning the date of its foundation, it is generally accepted that around the start of the Late Bronze Age Malthi was one of the pre-eminent settlements in the western Peloponnese. It commanded a strategic position on a high ridge in the Soulima Valley overlooking access routes to the Gulf of Kyparissia to the west as well as southward toward Nichoria via the Upper and Lower Messenian

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Plains (McDonald & Rapp 1972). Architecturally, one of the mainland's earliest terrace platforms supported the central cluster of buildings and a fortification wall (1.6–3.55 m thick and 420 m in length) surrounded the entire settlement (Valmin 1938, 16; Wright 1980, 60). Valmin's dating of various architectural elements, such as the fortification wall and the western 'magazines' abutting it, has been called into question and a later, LHIII, date for the zenith of occupation is probable (Darcque 1980, 32–3; Dickinson 1994, 60). Regardless of the exact timing of internal developments at the site, Malthi continued to be occupied through the palatial period (LHIII), at which time two tholos tombs were also constructed (Valmin 1938, 221). Scant traces of LHIIIC pottery in one of them attest to the last phase of Bronze Age occupation (Hope Simpson & Hagel 2006, 57).

The weights from Malthi are far from consistent in form or material, and from the very start there have been problems in identifying the artefacts from Malthi that should even be counted as weights (Valmin 1938, pl. XXVIII). Valmin identified over 300 objects that were, or could possibly be, used as weights (Valmin 1936–7; 1938). Petruso, reexamining the Malthi weights in his dissertation (1978, 134–41), limited his analysis to stone weights of recognizable types that had parallels in size, material and form elsewhere. I follow his approach and limit the study to the more secure examples. Unlike Petruso, however, I leave out possible weights made of schist in this analysis, since that material was not traditionally used to make weights. That leaves us with a catalogue of 48 objects (Table 4 & Fig. 2).

The interpretation of weights from Malthi is further complicated by two factors. The first is that weight sets that conformed to different standards appear there, and it is possible that some standards may have been in use simultaneously. In his publication of the site, Valmin attributed this variety to Malthi's position along major communication routes (1938, 385–8). He identified four main weighing systems in use and 'more or less evident traces' of three others (1938, 386). In his dissertation, Petruso narrowed down the range to two basic systems: one Minoan, represented by spheres, demi-spheres and sphendonoid weights that was based on a mina of approximately 491 g; and the other Mycenaean, represented by cubes and based on a 554.5 g mina (1978, 135–41). In my own investigation, I have been able to reconstruct sets based on three standards: the Minoan and Mycenaean ones outlined in detail by Petruso, as well as a set with a base unit of 8.3 g, likely conforming to a foreign system, that was identified by Valmin in his initial study (1936–7, 54).

The second factor complicating the interpretation of weights from Malthi is their depositional pat-

Table 4. *Catalogue of weights from Malthi considered in this study.*

Malthi inventory number	Mass (g)	Location	Shape	Material
7	206.4	A 5	Cube	Limestone
8	180.4	A 5	Cube	Haematite?
9	316.9	A 43	Sphere	Limestone
11	196.0	A 17	Cube	Haematite
117	52.5	A 43	Sphere	Limestone
140	188.9	D 44	Cube	Limestone
280	265.9	B 22	Cube	Limestone
339	383.9	B 31	Cube	Hard green
347	552.3	A 30	Cube	Limestone
411	4.5	B 18	Sphere	Haematite
434	183	B 43	Cube	Limestone
480	64.5	D 66	Cone	Limestone
633	224.7	A 43	Sphere	Limestone
640	308.8	B 41	Cone	Limestone
642	150.2	B 50	Sphere	Granite-like
690	191.4	B 22	Hemisphere	Limestone
691	122.0	D 70	Hemisphere	Limestone
699	49.8	?	Olive-shaped	Haematite
708	1032.6	B 39	Cube	Limestone
751	284.9	B 70	Cube	Haematite?
812	475.9	D 34	Sphere	Limestone
838	270.9	B 22	Cube	Limestone
953	280.2	A 17	Cube	Limestone
992	493.9	B 59	Sphere	Limestone
1000	212.0	B 99	Cube	Limestone
1011	145.7	C 52	Hemisphere	Limestone
1054	26.0	C 18	Sphere	Haematite
1057	286.9	C 14	Cube	Limestone
1076	230.0	C 8	Cube	Limestone
1107	83.4	B 94	Cone	Limestone
1124	16.5	B 104	Sphere	Haematite
1150	182.7	B 78	Cube	Limestone
1155	26.5	C 28	Cone	Haematite
1163	184.4	B 60	Cube	Limestone
1164	236.0	B 60	Cube	Limestone
1174	256.4	B 60	Sphere	Limestone
1175	198.3	B 60	Cone	Limestone
1223	128.5	B 70	Cone	Limestone
1237	29.8	B 56	Sphere	Haematite
1243	36.0	B 79	Sphere	Haematite
1248	16.8	B 79	Sphere	Haematite
1265	107.7	B 74	Cone	Limestone
1270	203.4	B 62	Cone	Limestone
1304	792.2	B 14	Cone	Limestone
1312	22.8	B 85	Sphere	Haematite
1326	16.5	A 17	Sphere	Haematite
1409	317.1	?	Cube	Granite-like
1410	320.8	?	Cube	Limestone

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Figure 2. *Plan of Malthi with locations of weights considered in this study. (After Valmin 1938.)*

terning, a direct result of the site's complex occupational history. Malthi was occupied for a number of centuries from the MBA through LBA and weights appear in the earliest levels of the settlement's occupation through to its final phase. There is evidence of set fragmentation, that is, the breaking up of early sets and the subsequent re-use of some of their weights in later ones. I hope to show that, despite the loss of information concerning its earlier context, knowledge of the formal and later contextual attributes of a weight set can be of assistance in re-assembling it even after it had been fragmented.

Due to the variability in depositional contexts and the heterogeneity of the clusters of weights, no coherent set is immediately as obvious at Malthi as the set found in the Vapheio tholos. Using traditional metrological techniques, we would not be able to make sense of this complex palimpsest and reconstruct sets of weights once they had been fragmented. However, by considering the factors outlined above, I have been able to reconstruct a few of these earlier sets and tentatively trace the use history of some of the weights in them. I begin by looking for points of congruence (i.e. similar shape, material or findspot). I then examine weights that may 'go together' and see if coherent sets can be assembled with them. Finally, once the sets have been reconstructed, I employ the methodology devised above to analyse their performance capabilities.

The masses of the Malthi weights range from 4.5 g to 1032.6 g. The pieces are mostly limestone, a number are haematite and a few are of another hard stone, perhaps granite. There is a preference for haematite in making lighter weights while limestone is preferred for heavier ones. Shapes include cubes, spheres, hemispheres and cones.

The dating of the weights is admittedly somewhat problematic. According to the excavator, 31 were found in MH contexts, 14 in LH levels and three were without context. Most of the contexts in which weights were found contained both MH and LH pottery. Often Valmin assigned a period to a weight based on his

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Table 5. *Masses and base units of the weights in the 'haematite set' at Malthi.*

Inventory number	Context	Shape	Attribution	Mass (g)	Ideal mass (g)	Error (±g)	Base unit (g)	Ideal base unit (g)
411	B18	Sphere	1/2	4.5	4.2	+0.3	9.0	8.3
1124	B104	Sphere	2	16.5	16.6	−0.1	8.3	8.3
1326	A17	Sphere	2	16.5	16.6	−0.1	8.3	8.3
1248	B79	Sphere	2	16.8	16.6	+0.2	8.4	8.3
1312	B85	Sphere	3	22.8	24.9	−2.1	7.6	8.3
1054	C18	Sphere	3	26.0	24.9	+1.1	8.7	8.3
1155	C28	Cone	3	26.5	24.9	+1.6	8.8	8.3
1237	B56	Sphere	4	29.8	33.2	−3.4	7.5	8.3
1243	B79	Sphere	4	36.0	33.2	+2.8	9.0	8.3
699	?	Olive	6	49.8	49.8	0	8.3	8.3
8	A5	Cube	22	180.4	182.6	−2.2	8.2	8.3
11	A17	Cube	24	196.0	199.2	−3.2	8.2	8.3
751	B70	Cube	34	284.9	282.2	+2.7	8.4	8.3

perceived construction date of the building in which it was found or by the earliest pottery type with which it was found (see Darcque 1980, 32–3 and Wright 1980, 60 n. 2, for similar problems concerning architecture). For example, the two weights found in Room A5 were in a context that included both MH and LHIII pottery that lay on top of a tomb that was sealed with LHI pottery in it, yet Valmin unequivocally assigned them to the MH period. However, as these weights were found above an LHI tomb, they could not have been deposited there during the Middle Bronze Age. In this case, the pre-LHI sherds found among the weights are not reliable chronological indicators. An LHIII date for the deposit, on the other hand, remains a possibility. Even when the contexts are less disturbed, one must be cautious in assigning dates to weights as post-depositional processes also play a role. Dense, smooth weights made during the LBA could have infiltrated MH levels even more easily than pottery did (Schiffer 2002). Likewise, considering how durable stone weights are, it is almost certainly the case that some MH weights were in use through the LBA. These caveats notwithstanding, there is sufficient clustering and stratigraphic resolution to permit an initial reconstruction of some of the weight sets used at Malthi.

Using the methods described above, I was able to reconstruct four sets of weights in use at Malthi during various periods. For reasons that shall become apparent, I have labelled them 1) the haematite set; 2) the rounded set (consisting of spheres, hemispheres and sphendonoids); 3) the cubed set; and 4) the central set. Since these different sets occasionally employ the same individual weights, they likely were not in use at the same time. I recognize three chronological phases during which the sets were in use. The first phase is represented by the haematite set, the second phase by the rounded and cubed sets, and the final phase by the central set. I provide the justification for this chronology in greater detail below.

Four weight sets from Malthi

1. The 'haematite set'

Uniform material is a desirable attribute among weights. Weights made of hard stones such as haematite were common throughout the Mediterranean in the Bronze Age. It is possible to reconstruct a coherent set using only the haematite weights from Malthi. Valmin labels these '*sidiropetra*' (1938, 380–82). I also include in my reconstruction of two weights (Inv. no. 8: 180.4 g and Inv. no. 751: 284.9 g) that he describes instead as 'hard black stone'. These weights are macroscopically indistinguishable from the *sidiropetra* ones and are easily distinguished from all of the other weights in Valmin's catalogue (1938, pl. XXVIII). Moreover, excluding them would cut the range of this set roughly in half, but would have no other effect on the set's integrity or accuracy.

The haematite set consists of 13 weights ranging in mass from 4.5 g to 284.9 g (Table 5). The average base unit is 8.3 g (equivalent in mass to a Mesopotamian shekel) with a normzone of 5 per cent. The range of the set without gaps is 16.8 g to 890 g in 4.1 g increments. This corresponds to a range from 2 shekels to 107.5 shekels in half-shekel increments. The average margin of error between the actual mass of any combination of weights and their ideal mass is 2.2 g with a range of error from 0 to 6 g. In the worst case, the error amounts to 8.4 per cent of the ideal mass of a particular value. The average increment between consecutive weights is 4.1 g, with a range of –0.4 to 8.2 g, and an average error of 0.97 g

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or 23 per cent with a worst-case error of 110 per cent. In roughly half of the cases, the incremental error is under 8 per cent. The general unevenness of the increments may seem problematic but it is important to keep in mind the degree of precision (under 5 g) that this set attempts to achieve. From that perspective, the haematite set at Malthi is impressively accurate and precise.

The haematite set is probably the oldest set of weights from Malthi. Its closest parallels were excavated in Early Bronze Age levels at Troy and Tarsus (Goldman 1956, 266–8, pl. 420 # 117–28; Schliemann 1880, 438). In all three instances, the haematite weights were irregularly shaped and roughly globular, not crafted in the characteristic sphendonoid shapes one sees elsewhere at Troy and throughout the eastern Mediterranean (see discussion of Gelidonya haematite sphendonoids above). In addition to material and shape, the base units of at least two of these sets are similar. The average base unit of the Tarsus set is 8.2 g (very close to Malthi's 8.3 g). Schliemann does not provide the masses of the weights from Troy and subsequent analyses (e.g. Bobokhyan 2006) do not separately inventory the non-sphendonoid haematite weights, which parallel those from Malthi and Tarsus. When scholars have treated the assemblage as a whole (e.g. Bobokhyan 2006), they have found that a Mesopotamian shekel of 8.7 g is one of a number of possible base units represented. Although haematite is found in the mountains near Malthi (Valmin 1938, 103) the conformity of this set to a supra-regional standard leaves open the possibility that these haematite pieces were imported.

2. The 'rounded set'

The next set which I reconstruct from Malthi is labelled the 'rounded set'. As Petruso deduced in his dissertation (1978, 138–41), these weights, consisting of spherical, demispherical and sphendonoids, form a set that conforms to the Minoan system of weighing. In this analysis, I exclude the schist examples included by Petruso, on the grounds that schist is not a material employed for weights elsewhere. I also exclude four additional weights that are superfluous (Malthi catalogue nos. 1174, 1243, 1248 and 1312). None of these four weights are neat multiples of the standard unit. This is understandable for the latter three, since they are of haematite, and might exclusively have belonged to the set detailed above. No. 1174 requires further explanation. Perhaps it was used as a 'cheat' in place of No. 633, a weight that was part of the set that was a mere 5 mm smaller in diameter but over 30 g lighter. Weight fraud is explicitly addressed in a number of Near Eastern law codes (Driver & Miles 1952, 183–4; VerSteeg 1998–9, 207) and it could easily have occurred in the Aegean.

The rounded set consists of 14 weights from 4.5 g to 493.9 g in mass (Table 6). The range of the set without gaps is 21 g to 2155.6 g in 20.5 g increments. This corresponds to 1/24 mina to just under 4 1/2 minas in 1/24 mina increments using the Minoan system. The set is based on a Minoan mina of approximately 492 g. The normzone is 4 per cent. The average margin of error between the actual mass of any combination of weights and their ideal mass is 5.7 g with a range of error from 0 to 16 g. In the worst case, the error amounts to 4 per cent of the ideal mass of a particular value. The average increment between consecutive weights is 20.5 g, with a range of 9.4 to 37 g, and an average error of 2.7 g or 13 per cent with a worst-case error of 80 per cent. In three-quarters of the cases, the incremental error is under 10 per cent. There are a few problems with its incrementation, suggesting that it is not an ideal set to monitor subtle gradations. Nevertheless, the figures suggest that the set is quite accurate overall.

In addition to these weights, Valmin discovered a bronze double axe tucked away in a niche in room B69 (1938, 178). The axe showed no signs of use and weighed 984.2 g, precisely the mass of a Minoan double-mina. He interpreted it as a votive offering, but considering the set of weights conforming to the same system, I suggest that the double axe was the prototype standard upon which the 'rounded set' was based.

3. The 'cubed set'

Petruso was also able to identify a set of weights, consisting of cubes, which conformed to the Mycenaean system of weighing (1978, 135–8). Most of the cubes are of limestone with a few of haematite. It is possible to reconstruct a coherent set of weights using 12 of the 20 cube-shaped stone weights catalogued by Petruso (Table 7). The range of the set without gaps is 363 g to 3292g in 23 g increments. This corresponds to 2/3 mina to 6 minas in 1/24 mina increments using the Mycenaean system (1N +4P to 3M in 1P increments as written in Linear B).

The set is based on a Mycenaean mina of approximately 548 g. The normzone is 1.5 per cent. The average margin of error between the actual mass of any combination of weights and their ideal mass is 20.6 g with a range of error from 2 to 42 g. In the worst case, the error amounts to 3.4 per cent of the ideal mass of a particular value. The average increment between consecutive weights is 22.9 g, with a range of 9.3 to 34 g, and an average error of 3.7 g or 16 per cent with a worst case error of 149 per cent. In roughly half of

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Table 6. *Masses and base units of the weights in the 'rounded set' at Malthi.*

Inventory number	Context	Material	Attribution	Mass (g)	Ideal mass (g)	Error (±g)	Base unit (g)	Ideal base unit (g)
411	B18	Haematite	0.25	4.5	5.1	−0.6	18.0	20.5
1124	B104	Haematite	0.75	16.5	15.4	+1.1	22.0	20.5
1326	A17	Haematite	0.75	16.5	15.4	+1.1	22.0	20.5
1054	C18	Haematite	1.25	26	25.6	−0.4	20.8	20.5
1237	B56	Haematite	1.5	29.8	30.8	−1.0	19.9	20.5
699	?	Haematite	2.5	49.8	51.3	−1.5	19.9	20.5
117	A43	Limestone	2.5	52.5	51.3	+1.2	21.0	20.5
691	D70	Limestone	6	122	123.0	−1.0	20.3	20.5
1011	C52	Limestone	7	145.7	143.5	+1.8	20.8	20.5
690	B22	Limestone	9	191.4	184.5	+6.9	21.3	20.5
633	A43	Limestone	11	224.7	225.5	−0.8	20.4	20.5
9	A43	Limestone	16	316.9	328.0	−10.1	19.8	20.5
812	D34	Limestone	23	475.9	471.5	+4.4	20.7	20.5
992	B59	Limestone	24	493.9	492.0	+1.9	20.6	20.5

Table 7. *Masses and base units of the weights in the 'cubed set' at Malthi.*

Inventory number	Context	Material	Attribution	Mass (g)	Ideal mass (g)	Error (±g)	Base unit (h)	Ideal base unit (g)
8	A5	Haematite?	8	180.4	182.4	−2.0	22.6	22.8
1150	B78	Limestone	8	182.7	182.4	+0.3	22.8	22.8
1163	B60	Limestone	8	184.4	182.4	+2.0	23.1	22.8
7	A5	Limestone	9	206.4	205.2	+1.2	22.9	22.8
1000	B99	Limestone	9	212.0	205.2	+6.8	23.6	22.8
1076	C8	Limestone	10	230	228.2	+1.8	23.0	22.8
1164	B60	Limestone	10	236	228.2	+7.8	23.6	22.8
280	B22	Limestone	12	265.9	273.6	−7.7	22.2	22.8
838	B22	Limestone	12	270.9	273.6	−2.7	22.6	22.8
1409	?	Granite-like	14	317.1	319.2	−2.1	22.7	22.8
347	A30	Limestone	24	552.3	547.2	+5.1	23.0	22.8
708	B39	Limestone	45	1032.6	1025	+7.6	22.9	22.8

the cases, the incremental error is under 6 per cent. As with the rounded set, there are a few problems with its incrementation, but the set is generally accurate overall.

The conformity of the cubed set to the notational system employed in the Linear B tablets is noteworthy and adds confidence to its reconstruction. There is no evidence, however, that the script was in use as early as these weights were. Rather, I would suggest that the script, whenever it was first developed, conformed to a sexagesimal weighing system that was already in place.

Originating in the MH period with most pieces surviving into the LHIII, the cubed and rounded sets occupy the middle position chronologically. They may have been used contemporaneously, with shape as a readily identifiable indicator of the standard to which each conformed: rounded for the Minoan standard, cubed for the Mycenaean. Alternatively, they may have been used in succession, straddling the time when the Mycenaean weight standard succeeded the Minoan one (Alberti 2006). The stratigraphic contexts of the weights in the two sets are somewhat helpful in determining their sequence. Four of the 14 weights in the rounded set can be dated with some degree of confidence based on associated pottery. Of these, two come from MH strata (Malthi nos. 812 and 1326) and two from LH strata (Malthi nos. 1011 and 1237). Of the 12 weights in the cubed set, 5 are securely dateable (Malthi nos., 7, 8, 347, 1163, 1164) and they all belong to the LH period. One cubed weight (Malthi no. 140), not included in my reconstruction, was recovered from an MH context. Overall, though, there is a recognizable correlation between date and shape. The overlap of the standards at Malthi is noteworthy, as it represents the only instance where sets adhering

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Table 8. *Masses and base units of the weights in the 'central set' at Malthi.*

Inventory number	Context	Material	Shape	Attribution	Mass (g)	Ideal mass (g)	Error (±g)	Base unit (g)	Ideal base unit (g)
1155	C28	Haematite	Cone	1	26.5	23.1	+3.4	26.5	23.1
117	A43	Limestone	Sphere	2	52.5	46.2	+6.3	26.3	23.1
1223	B70	Limestone	Cone	5	128.5	115.5	+13.0	25.7	23.1
8	A5	Haematite?	Cube	8	180.4	184.8	− 4.4	22.6	23.1
7	A5	Limestone	Cube	9	206.4	207.9	− 1.4	22.9	23.1
633	A43	Limestone	Sphere	10	224.7	231.0	− 6.3	22.5	23.1
751	B70	Haematite?	Cube	12	284.9	277.2	+7.1	23.7	23.1
9	A43	Limestone	Sphere	14	316.9	323.4	+6.5	22.6	23.1
347	A30	Limestone	Cube	24	552.3	554.4	− 2.1	23.0	23.1

to both Minoan and Mycenaean standards exist at one site.

4. The 'central set'

Proximity is a consideration in reconstructing sets of weights and there are a few clusters of weights at Malthi (Fig. 2). One of these, close to the site's peak, forms a coherent set. The central set consists of nine weights of various shapes and materials ranging in mass from 26.5 g to 552.3 g (Table 8). It conforms to the Mycenaean system of weighing. The weights that compose the set were found in and around the central building, dubbed by Valmin 'the Palace' at the acropolis of the site. While Valmin assigned MH dates to some of the weights (possibly based on form), stratigraphic analysis reveals that all of the weights in this set come from excavation contexts that date to the last phase of occupation of the settlement. In some cases, they are found with clearly identifiable LHIII pottery, in others they appear in rooms that were in use during the last phase of the site's occupation. Three additional weights (nos. 11, 953, 1326), all found in excavation unit A17, are excluded from this set. They were all found underneath a layer of stones that formed the pavement of this courtyard, and separated the LH stratum from the previous ones (Valmin 1938, 94). None of them conforms individually to the Mycenaean system but, interestingly, their masses add up to 1 Minoan mina. They may have been part of an earlier set. The range of the LHIII central set without gaps is 180.4 g to 1818.1 g in 23 g increments. This corresponds to 1/3 mina to 3 1/4 minas in 1/24 mina increments using the Mycenaean system (8P to 1M + 2N + 6P in 1P increments as written in Linear B).

The set is based on a Mycenaean mina of approximately 554 g. The standard mina upon which this set is based is a few grammes heavier than that of the cubed set but falls within the general range of Mycenaean mina weights elsewhere. The discrepancy is most likely due to imprecision in the execution of the physical weights themselves rather than any shift in the actual standard. The normzone is 3.2 per cent. The average margin of error between the actual mass of any combination of weights and their ideal mass is 7.1 g with a range of error from 0.1–24.1 g. In the worst case, the error amounts to 4.1 per cent of the ideal mass of a particular value and in two-thirds of the cases the error is under 1 per cent. The average increment between consecutive weights is 23.4 g, with a range of 0.1–34.2g, and an average error of 5.52 g or 24 per cent with a worst-case error of 101 per cent. In roughly three-quarters of the cases, the incremental error is 20 per cent or less. As with the other sets, despite problems with incrementation the central set is accurate enough for most Bronze Age weighing needs.

I consider the central set to be the latest ones in use at Malthi. All the weights in these sets were found in contexts that are likely, or at least possibly, LHIII. Conversely, there is no direct evidence whatsoever to suggest that any of the weights in this set were deposited *prior* to the LHIII period. The clustering of the weights that form the set suggests that they were in use together prior to their final deposition. It was an *ad hoc* set, pieced together from elements of other sets that had previously been fragmented.

Given the complex history of the site and the diachronic changes in the types of weights used and the even the weighing standards to which those weights conformed, my proposed reconstructions of the Malthi weight sets are more tentative than those at Vapheio and Cape Gelidonya. Vapheio is a discrete deposit and there is no compelling reason to interpret the weights there as anything but a set. The typical sphendonoids from the Gelidonya wreck were found together with other weights, but the method presented here permits us to identify which ones belonged with each other in a set. At Malthi, the

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results are less obvious. Since all the haematite pieces recovered by Valmin form a serviceable set of weights, we can be confident in the reconstruction of that set. The rounded and cubed sets, on the other hand, were culled from a larger assemblage. We must still explain the presence of the superfluous weights. I offer that there were likely multiple sets of these two types and that the sets I have reconstructed are better interpreted as representative of the types of weight sets that could have been assembled at Malthi from the available weights. Similarly, the central set, consisting of a cluster of weights with no superfluous pieces, is a good candidate. The fact that these reconstructed sets conform to known metrological systems adds confidence to their validity.

Discussion

By reconstructing sets of weights and by adopting criteria that can be used to analyse them, we can better understand how well they performed the tasks for which they were made. Table 2 summarizes some of the data concerning the accuracy and precision of the sets of weights analysed here. Certain patterns emerge when we consider those variables. In sum, each set described above falls well within the tolerances of accuracy for Aegean weights published elsewhere. Indeed, the normzones at Malthi are far tighter than most (compare normzones calculated by Petruso 1992). I attribute this accuracy not to the overall skill of the craftspeople who manufactured Malthi's weights as much as to the method of isolating pieces that belong together. We should expect greater conformity among weights from the same set than weights from different sets, even if the latter are all found at the same site.

As an independent test of this hypothesis, consider the weights from Ayia Irini published by Petruso (1992). He calculated 61.6 g for the mean unit in use and an 8 per cent normzone. I recalculated the mean resulting unit for a number of subsets of his catalogue, taking into account factors such as material and stratigraphic context. The mean unit for lead disks alone, regardless of fractional attribution, is 61.8 g with a normzone of 7 per cent. Subdividing this assemblage into discrete archaeological strata, those exclusively from Period VI have a mean of 61.3 g and a normzone of 5.8 per cent and those exclusively from Period VII have a mean of 61.0 g and a normzone of 6.5 per cent. Thus, comparing weights that belong together using the criteria I outline above reveals more coherent sub-assemblages of weights. That is, they achieve greater precision and are chronologically more discrete. I suggest that the weights grouped with such criteria in mind were more likely to have been used together.

A second pattern that emerges from the reconstruction and analysis of the sets is that, while they are accurate, they are extremely imprecise. While a given combination of weights can approximate its ideal mass quite well, there are great fluctuations in the spacing between increments in these sets. As a result, certain types of weighing are not possible with any degree of confidence. For example, if one wished to compare two similarly sized lumps of bronze, it would not be possible to calculate with any precision the difference between their masses using these sets. You could say, 'this piece weighs about a mina, while the other one weighs less,' but you could not employ the sets to determine if the difference between the two was, say, 60 g or 80 g. Such imprecision plagues ancient weight sets, and the sets from the Bronze Age Aegean are not alone in having this problem.

Conclusions

With the exception of Renfrew's integration of metrology into the broader sub-field of Cognitive Archaeology (e.g. Renfrew 1994; 2012), the study of weights has been limited to their intrinsic properties. While such work is foundational and important, there remain broader avenues of research that archaeometrologists have yet to explore. One reason for the narrow framework of research has been the emphasis on the individual weight, rather than the weight set, as the primary unit of analysis. In this article, I have attempted to show the benefit of shifting the focus of metrological investigation from individual weights to sets of weights.

Thinking about weights in this way opens up useful avenues for research. Understanding certain characteristics of weight sets, such as their range, incrementation and internal consistency, provides a framework through which archaeologists can reconstruct sets of weights effectively as well as pose hypotheses concerning the socio-economic context in which weighing occurred. Formal properties such as raw material and artistic quality can provide further insights into some social aspects of weighing (Rahmstorf 2006, 9–10). For instance, the social context in which weighing takes place determines the kind of set that is acceptable. In a private context, when a person wishes to confirm the mass of a delivery, all that really matters is that they know the mass of each weight and that they know how to add. In such a case, an *ad hoc* set with weights of varying forms or materials can be

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satisfactory. Weighing in public, as in a marketplace, is a performative act with broader social intricacies. In such contexts, using weights that are standardized (i.e. identical in form and in mutually recognized units), and are therefore legible (*sensu* Scott 1998), provides transparency in the weighing process and builds trust between the parties. As the primary goal has heretofore been to identify a normative unit, researchers have not fully explored the analytical potential of such variables.

Another opportunity provided by the method outlined here concerns examining the role of weighing in the political economies of complex societies. Tracing changes in the weight sets at Malthi as well as changes in their use illustrates this point. For instance, the haematite sets discussed in this article, with their light capacity, narrow range, fine increments and pan-eastern Mediterranean standards, are suited for weighing luxury commodities that were part of an interregional trade network. The later three sets from Malthi, with their higher capacities, wide ranges, coarser incrementations, and regional standards, were better suited to weighing bulk goods. This change in economic activity corresponds to broader shifts in the region's economy, but this topic must be reserved for another study. Focusing on weight sets, as opposed to individual weights, enables us to recognize such changes in the first place.

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