Experimental Archaeology and Siege Warfare:
Analysing Ancient Sources through Experimentation

A thesis submitted to the University of Manchester for the degree of
Doctor of Philosophy
in the Faculty of Humanities

2014

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SCHOOL OF ARTS, LANGUAGES AND CULTURES
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Abb. Abbildung (Illustration)
Aelian, Tact. Aelian, On the tactical array of the Greeks
(Περί Στρατηγικών Τάξεων Ελληνικών)
Appian, Mith. Appian, Mithridatic Wars
BNJ Brill's New Jacoby
c. circa
Cicero, ad Q. Fr. Cicero, ad Quintum Fratrem
D Diameter of the spring-hole (see Glossary)
ed. (eds.) Editor (Editors)
e.g. For example, exempli gratia
ff 'and following' (after a page number)
F GH Jacoby’s Die Fragmente der Griechischen Historiker
Fig. Figure
g Gramme (measure of weight)
Iamblichus, Via Pyth. Iamblichus, On the Pythagorean Life (De vita pythagorica)
i.e. That is, id est
IG Inscriptiones Graecae
in. Inch (measure of length)
lb Pound (measure of weight)
LSJ Liddell-Scott-Jones Greek-English Lexicon
mm Millimetre (measure of length)
NB Note well, nota bene
Pliny, Nat. Hist. Pliny, Naturalis Historia
Polyaenus, Strat. Polyaenus, Strategemata
pref. Preface, Praefatio
Quintilian, Inst. Orat Quintilian, Institutio Oratoria
trans. Translated by
UCL University College London
Vol. Volume
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Abstract

This thesis seeks to show that by using the principles of experimental archaeology it is possible to reconsider the extent to which the ancient writers understood the use of artillery in the field and under siege conditions. A combination of philological and experimental approaches has been taken to determine not only how catapults could be used by Hellenistic armies, but also why certain actions were taken when artillery was brought into the field. The experimental approach is discussed throughout the thesis, with attention drawn to its merits and disadvantages, and how these can be used to improve the methodologies through which we can further develop our understanding of Hellenistic military history and technology.

There are three main sections to the thesis. The first takes a philological approach to considering the ancient artillery treatises by Philon, Heron, and Biton, with reference to Vitruvius' work on catapults. Each treatise is assessed with regard to its level of technicality and the extent to which it can be used for the purpose of constructing catapults. The treatises are then used in the second part of the thesis to construct functional replicas of the Hellenistic stone-thrower and the Hellenistic bolt-shooter. In the third part of the thesis, the catapults are tested against the ancient writers' descriptions of their use in the field.

The findings of this thesis show that the ancient writers were broadly accurate in their descriptions of catapult use, but that they appear to be largely unaware of the reasoning behind their deployment. The thesis also highlights problematic parts of the technical treatises which previous scholars have ignored, in particular gaps in the descriptions of some components necessary for the catapults to function. Moreover, solutions are offered to complete the gaps left by the technical writers, especially where none are offered by the commentaries on these works. This thesis also demonstrates that catapults had a specific function in Hellenistic warfare which focused largely on sieges and static engagements. Most importantly, however, this thesis shows that not only can practical experimental methods successfully be applied to otherwise text-based research, but that it produces significant results which can aid in our understanding of military history, ancient technology, and the reliability of the ancient writers.
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Acknowledgements

There are many people without whose support and encouragement this thesis would never have come to completion. At the top of that list are John and Esdi Hughes, who are the best friends anyone could wish for. They have offered me their time, energy, workshop facilities, ideas, and skills, and they have opened up their home to me on numerous occasions. I cannot thank them enough for their support, kindness, encouragement, and general craziness. Special congratulations should go to Esdi, who achieved the furthest range and the best accuracy during testing. Thank you, guys!

I would also like to thank my supervisor, Dr. Andrew Fear, and the members of my supervising panel, Dr. Peter Liddel and Prof. David Langslow, for all the advice, encouragement, and support they have given me.

Thanks go also to my family – my partner, Dr. Benjamin Lee, my parents, Roy and Lynn Schofield, and my parents-in-law Ken and Glynis Lee – for their continuing support.

Without a place to construct the catapults and to test them, this project would never have gone anywhere. I would like to thank Dennis Hughes and Son (Metals) Ltd for allowing me to use its land and facilities throughout the project (http://www.d-hughes-metals.co.uk/). I am very grateful to Helen Hughes of New Hall Farm, Newhey, who allowed me to use a field for testing the range of the bolt-shooting catapult. I would also like to thank Philmar Fabrications, who made the flanges for the washers (http://www.philmar.co.uk/). Chris Hanson also deserves thanks for his help in some of the wood cutting and for constructing the boxes for the trigger mechanisms. Hazel Burke very generously allowed me to use her gazebo for the initial testing of the bolt-shooting catapult, to prevent it (and the operators) from being damaged by rain, and I am very grateful to her.

There are a number of members of the re-enactment community in addition to John
and Esdi Hughes who also deserve a special mention here for their support and encouragement, especially (and in no particular order) Myk Dormer, Andrea Bowes, Liza Graham, Paul and Jenny Garside, John Winder, and Gary Foster. Thanks also go to the Ermine Street Guard for the information they provided for me with regard to their bolt-shooting catapults – in particular I would like to thank Chris Haines, Tom Feeley, Tony Segalini, and Rob Ingram.

Funding is essential if projects like this are to be made possible. I would like to thank the Lloyd Trust for giving me an initial grant to help me purchase materials to construct the catapults. I would also like to thank the University of Manchester for supporting me from my second year onwards with a University Research Scholarship, covering my fees and providing me with a maintenance allowance.

Of those people whom I have met through the University of Manchester's Classics and Ancient History Department, there are many people I would like to thank for their support, including Sarah Brooks, Melissa Markauskas, Dr. Terry Abbott, Dr. Jason Crowley, Stevie Spiegl, Lizzie Pearson, Marci Freedman, Dr. Amy Coker, and David Paul Anderson. I would particularly like to thank the members of academic staff who set me on this path and guided me though my undergraduate and masters degrees, especially Dr. Polly Low, Dr. Andrew Morrison, Prof. Tim Parkin, Dr. Roberta Mazza, Prof. Stephen Todd, Dr. John Briscoe, and Dr. John Prag. Thanks go also to those people not listed here who have supported me throughout my time at Manchester.
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**Introduction**

Experimental archaeology, that is the reconstruction of objects based on finds or textual evidence for the purpose of experimentation and analysis, is a form of research which has been used for over one hundred years, \(^1\) yet Trigger has argued that 'No one has ever considered replicative experiments as other than archaeological', and that 'their relevance for archaeological interpretation, *and for it alone*, is unquestioned'. \(^2\) This is not the case: experimental archaeology has been used by scholars of various other disciplines, including Classics and History, to shed fresh light on their own areas of research and to make their subjects relevant and informative to the public through outreach work. This thesis seeks to question Trigger's assertions further, and to show that reconstruction can have a wider relevance for our understanding of history and ancient texts than simply a consideration of the material culture of the past. Specifically, this thesis will show that the reconstruction of catapults based on a combination of textual and archaeological evidence can deeply affect our comprehension of military history in the Hellenistic age; by reconstructing early catapults, this thesis intends to explore, and if necessary correct, the ancient historians' descriptions of the use of catapults. \(^3\) The questions which will be addressed, therefore, are as follows: first, is the use of reconstructions, based on technical treatises and archaeological evidence together, a suitable way to approach the question of the reliability of the ancient historians who wrote the military history of the Hellenistic period? Second, using this methodology, what can we learn about the reliability of the technical writers and historians in their narratives where catapult technology is concerned, and does this have wider implications for our understanding of how artillery was used in the ancient world? Finally, what can the reconstructions themselves tell us about catapults?

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\(^1\) For examples of its use, see below.

\(^2\) Trigger (2006), 371 (my italics).

\(^3\) The term 'historians' is used here and elsewhere in this thesis as a cover-all term for the ancient writers whose works were drawn upon to supply the raw data for the testing phase of this project. It should be noted that it includes writers of other genres, including biography.
and their use on the ancient battlefield?
Historical Context

Before explaining the methodology of this thesis, the historical and scholarly contexts into which it fits must be considered. The chronological background of the catapult is, partly, problematic. Diodorus Siculus claims that the catapult was developed at the court of Dionysius I of Syracuse between 399 and 397 BC. Diodorus' choice of vocabulary (καταπελτικόν, a general and unspecific term for 'artillery') does not tell us whether he means the development of tension-based artillery (the *gastraphetes*) or torsion-based artillery. There has been a great deal of scholarly debate, therefore, concerning which type of 'catapult' he means. Schramm insisted that Diodorus was describing the development of torsion artillery, but there is now a general consensus that it is actually the *gastraphetes* to which he refers. Moreover, there is some question over the accuracy of Diodorus' dating of the invention of the catapult to this period. As Cuomo has noted, aetologies for several military technologies which Diodorus gives seem to have alternatives in other writers, which suggests that Diodorus may not always be as accurate as we might like.

Further problems in establishing an accurate date and location for the invention of the catapult emerge from the fact that several pieces of evidence suggest that catapults of some form were in existence prior to the fourth century BC. First, an Assyrian relief from the ninth century BC may or may not show a catapult; however, the image is unclear and is therefore not conclusive proof that catapults had been developed by that time. It seems more likely that it represents a battering-ram or some form of hooking device to take hold

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4 All ancient authors names are given in their conventional forms. The names of the technical authors are written as in Marsden (1999) for easy cross referencing. Fragmentary authors' names are given as found in BNJ, again for easy cross referencing.
5 Diodorus Siculus, XIV.42.1 and XIV.50.4.
6 See LSJ under καταπελτικόν for the definition of this word.
7 Diodorus Siculus, XIV.42.1. For information on the *gastraphetes* see Glossary and below.
8 Schramm (1980), 18.
10 Cuomo (2007), 44-45.
11 See Marsden (1969), Plate 3.
of a city wall. Secondly, 'stone balls that could be catapult projectiles have been found at Paphos and Phocaea', though such rocks could have had other uses for the besieged. Textual evidence also suggests that catapults may have been in existence before the fourth century BC. Biblical references to the use of catapults, suggest that mechanical artillery was in existence well before the time in which Diodorus places them. The writer of Chronicles, who claimed that catapults were invented in the ninth century BC, wrote in the late fourth century BC; by this stage, we have strong evidence from numerous sources that catapults had become widespread in the Mediterranean world, including, as a result of Alexander's campaigns, the Near East. Moreover, the chronicler has a reputation among scholars for being 'uniformly unreliable'. Therefore, given the strong likelihood of anachronism on his part, there is a consensus that his evidence is highly likely to be incorrect. The evidence from Ezekiel may be dismissed more simply as an anachronistic mistranslation; the original Hebrew text ought to be translated, according to Marsden, as 'karim which means battering-rams' rather than the more advanced siege machinery available when the text was translated into Greek.

We also have some references to the existence of catapults prior to the fourth century BC made by later writers. Polyaeus, for example, writing in the mid-second century AD, describes the use of bolt-throwing catapults at Cambyses' siege of Pelusium in 525BC. Rihll dismisses this assertion as anachronistic, without any stated basis, though she likens it to the anachronism found in Chronicles. Pliny claims that catapults were developed by the Phoenicians, and given the numerous interactions between the Greek

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13 Cuomo (2007), 45. See also Rihll (2007), 30. NB: all place names given in this thesis conform to the spellings found in the OCD for ease of cross-referencing, except in direct quotations where the original author uses an alternative form of the name.
14 Chronicles 2.26.15, and Ezekiel 4.2 and 21.2.
16 See below for discussion of the use and spread of catapults in this period.
17 Alexander (1946), 209.
19 Marsden (1969), 53.
22 Pliny, Nat. Hist. 7.81: 'they say that the son of Jupiter invented the Scythian bow and arrow, and that the
and Carthaginian Sicilians, the introduction of the catapult to the Greek world via a Phoenician connection would certainly be plausible, but only if there were substantial evidence to show that the catapult had been developed there. For this, Pliny is our only source, and, as Rihll argues, he 'lacks any supporting evidence'. Pliny's own source is unknown. Additionally, there is linguistic evidence to suggest that Pliny is incorrect: as Rihll notes, the way in which the word for catapult (καταπάλτης) is formed is wholly Greek in origin, rather than showing linguistic features from a foreign source as would be expected if the catapult had been developed outside of the Greek world and then imported.

In terms of the date of the catapult, too, it has been seen as highly unlikely that Thucydides would have neglected to mention, if not discuss in detail, catapult technology had it been present in the Greek world during his time, when he spends a great deal of time in the consideration of weaponry such as the Boeotian flame-thrower, the innovative techniques used at the siege of Plataea, and the siege of Syracuse, especially the development of new ramming techniques – and the rams themselves – during the naval battles in Syracuse's harbour. The fact that he fails to mention catapults at Syracuse, despite his evident interest in the technological developments which the Syracusans used in their defence of the city, at a time when, if Pliny were correct, we would expect catapults to be in evidence there, suggests that the technology was not available then. However, it

Persian son of Perseus invented other arrows, Aetolian spears, the Aetolian son of Mars invented the javelin with a strap, the Etruscan son of Mars invented the spear of the Velites, the same man invented the pilum, that Penthesilea the Amazon invented the battle-axe, the Pisean invented the hunting-spear and the scorpion in its twisted ropes, the Cretans the catapult, the Syrophoenicians the ballista and the sling... (arcum et sagittam scythen iovis filium, alii sagittas persen persel filium invenisse dicunt, lanceas aetolos, iaculum cum ammento aetolum martis filium, hastas velitares tyrrenum, eundem pilum, penthesileam amazonem securim, piseaeum venabula et in tormentis scorpionem, cretas catapultum, syrophoenicas ballistam et fundam...). See also Marsden (1969), 53-54, Alexander (1946), 210, and Rihll (2007), 29.

27 Thucydides, 4.100. See also Marsden (1969), 51.
28 Thucydides, 2.75-77. See also Marsden (1969), 49-50.
30 E.g. at Thucydides, 7.34, where adapted rams were used on the ships in the naval battle.
31 Marsden (1969), 50.
should be acknowledged that this is an argument *ex silentio*, albeit a compelling one.

In light of this, and the other arguments set out above, Diodorus' account of the invention of the catapult certainly seems to be the most plausible of those on offer. Moreover, his source, Philistus, was closely linked to Dionysius I, and was present at his court; for this reason, Diodorus' account has been considered authoritative. Ancient authors, including Cicero and Quintilian, deemed Philistus to be a historian comparable to Thucydides. Diodorus' use of Philistus, and his own Sicilian origins, may call into question his agenda in attributing the invention of the catapult to a Sicilian tyrant. It may be the case that Diodorus, or Philistus before him, here plays up Sicilian involvement in the catapult's development to promote his own people; this is, nevertheless, also an argument from silence. Cuomo is right to caution against blind acceptance of Diodorus' assertion that the catapult was invented in Syracuse at that time; but the evidence provided by Diodorus is the best that we have for a date and place of origin for the catapult, and there is relatively little reason to disbelieve him.

The catapult appears to have arrived on the Greek mainland at some point in the first half of the fourth century: Plutarch tells us that Agesilaus witnessed a catapult demonstration in the 360s BC, while Aeneas Tacticus, writing at this time, gives a single brief reference to catapults (καταπάλται). As this is the only time he mentions such devices, it has been suggested that catapults were not widespread at this point, which in turn affects how modern scholars have perceived the spread of catapult technology throughout the Mediterranean. However, as this argument is to all intents and purposes from silence, it is of limited value in trying to establish the time at which catapult technology became commonplace. Whether the catapult developed in a linear or more

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34 Cuomo (2007), 46.
35 Plutarch, *Regum et imperatorum apophthegmata* 62.1. See also Cuomo (2007), 41.
36 Aeneas Tacticus, 32.8. See also Whitehead (2003), 195.
38 Cuomo (2007), 42.
sporadic fashion is disputed;\textsuperscript{39} however, it is clear that between the fourth and the second centuries BC, the catapult's structure and the source of its power, and the types of uses to which it was put changed considerably.

More evidence for the presence of the catapult in Greek poleis is available for the second half of the fourth century BC. We have epigraphic evidence which shows that catapults were known in Athens from the mid-fourth century: one inscription, which forms part of a gravestone for a καταπελταφέτης (someone who shoots catapults), was set up at some time between 350 and 340BC.\textsuperscript{40} Another from the naval dockyards lists catapult parts present at Athens at this time, though the year in which the inscription was set up is disputed; the latest proposed date for the inscription is 326BC.\textsuperscript{41} The meanings of the parts listed are also under dispute: Marsden claims that they represented early torsion spring-frames along with several non-torsion pieces,\textsuperscript{42} while Rihll argues that it is much more likely that the inscription refers purely to non-torsion artillery.\textsuperscript{43} The key terminology under dispute is πλασία, which Marsden translates as 'catapult-frames',\textsuperscript{44} but Rihll translates as sliders;\textsuperscript{45} σολήνες, which Marsden translates as 'the early or Attic equivalent of σῦργης, the fixed stock',\textsuperscript{46} but Rihll translates as the 'cases';\textsuperscript{47} and ἐπιστύλια, which Marsden translates as 'the early or Attic version of περίτρητα, hole-carriers',\textsuperscript{48} but Rihll translates as 'belly-bars'.\textsuperscript{49} Marsden and Rihll agreed on several of the terms, however. Both accept that βάσεις refer to the 'bases' of catapults, and that the τόξα ἐσκυτωμένα are 'bows' wrapped or encased in leather.\textsuperscript{50} The main problem with Marsden's translations is that, as Rihll points

\textsuperscript{39} Cuomo (2007), 46 and 48-49.
\textsuperscript{40} Rihll identifies this inscription as IG II\textsuperscript{2} 3234 which seems to be incorrect. I have not been able to identify the correct inscription. See Rihll (2007), 63, and 63 n. 43.
\textsuperscript{41} IG II\textsuperscript{2} 1627 B, lines 328-341. See Rihll (2007), 64-66 and 69-70, and Marsden (1969), 56-57. See also IG II\textsuperscript{2} 1422 and IG II\textsuperscript{2} 120 which are dated slightly earlier: Cuomo (2007), 46, and Winter (1971), 219.
\textsuperscript{42} Marsden (1969), 60-61.
\textsuperscript{43} Rihll (2007), 66.
\textsuperscript{44} Marsden (1969), 60.
\textsuperscript{45} Rihll (2007), 69.
\textsuperscript{46} Marsden (1969), 60.
\textsuperscript{47} Rihll (2007), 69.
\textsuperscript{48} Marsden (1969), 61.
\textsuperscript{49} Rihll (2007), 69.
\textsuperscript{50} Marsden (1969), 60-61, and Rihll (2007), 69.
out, he is willing to assign 'unique meanings to [the] words' which 'is, in principle, a dodgy procedure', the meanings Marsden gives to the some of the words in the inscription are otherwise unattested, and do not necessarily make sense in that context. Moreover, the τόξα ἐσκυτωμένα, which occur in the middle of the list, do not dissuade Marsden from asserting that at least some of the parts listed are connected with torsion catapults, rather than the whole list, as Rihll argues, being non-torsion catapult parts. On the whole Rihll's argument is more linguistically plausible than Marsden's in this instance. Therefore, if her argument is accepted, it can be said that non-torsion catapults at least were present in Attica by the end of the third quarter of the fourth century.

In addition to the epigraphic evidence, Diodorus, along with other historians, tells us that catapults were used at sieges throughout this period. Several possibilities for the method by which catapult technology was spread throughout the Greek world have been suggested: one is that the craftsmen employed by Dionysius I of Syracuse may, after his death, have sought employment outside Sicily and taken their knowledge of the construction of catapults with them. Another possibility is that Dionysius may have passed the technology to allies, possibly including the Athenians, and the technology spread from there. Alternatively, Diodorus may be wrong in asserting that the catapult was invented solely at Syracuse, and there may have been several groups or individuals developing the technology in different parts of the Mediterranean.

51 Rihll (2007), 65.
52 IG II² 1627 B, lines 332-333
54 For example at Motya – Diodorus Siculus, XIV.50.4; Perinthus – Diodorus Siculus, XVI.74.4-5 and XVI.75.3; Halicarnassus – Arrian, The Campaigns of Alexander 1.20 and 1.22; and Tyre – Arrian, The Campaigns of Alexander 2.23, Diodorus Siculus, XVII.42.7, XVII.43.1 and XVII.45.2, and Curtius Rufus, The History of Alexander 4.3.13. See also Schofield (2009), 49-50 and 53-54.
57 Cuomo (2007), 55-56.
Development of the Catapult

The first stage in the development of the catapult was, according to Heron, the **gastraphetes**.\(^{58}\) This was non-torsion, built using a bow with a heavier draw-weight than a manual bow since Heron tells us that it was 'too strong for withdrawal by a man's hand.'\(^{59}\) Later models of artillery were torsion-powered, with twisted rope-springs used to provide the propulsion for the missile.\(^{60}\) When this change actually took place is unclear. Marsden believes that it happened by the siege of Tyre in 332BC, because this is the first siege at which we have evidence of stone throwing catapults being used against walls.\(^{61}\) However, neither of our sources states directly that this was the first siege ever at which catapults were used for this purpose.\(^{62}\) Other changes to the catapult over this time period include the introduction of washers to protect spring-frames, changes to the relative dimensions of the spring-frames themselves, and the use of two different types of frames – **palintone** (παλίντονος) and **euthytone** (εὐθύτονος) – for stone- and bolt-throwing catapults respectively.\(^{63}\)

As the catapult developed, it had a great impact on how siege warfare was fought, and can be argued to represent a 'Revolution in Military Affairs' (RMA). This theory postulates that improvements or innovations in military technology can bring about huge changes in the practice of warfare: Lonsdale suggests 'gunpowder … airpower and nuclear' as examples.\(^{64}\) Moreover, an RMA 'requires new tactical and operational concepts'.\(^{65}\) the technological development on its own does not constitute an RMA. This theory is usually applied to modern forms of warfare; Lonsdale here applies it to the army and strategy of

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\(^{58}\) Heron, *Belopoeica* 75.2-9.
\(^{59}\) Heron, *Belopoeica* 75.11: βιαιοτέρας τῆς διὰ τῆς χειρὸς τοῦ ἀνθρώπου γεγονομένης καταγωγῆς.
\(^{61}\) Marsden (1969), 103.
\(^{62}\) Diodorus Siculus, XVII.42.7, and Curtius Rufus, 4.3.13.
\(^{63}\) Marsden (1969), 43.
\(^{64}\) Lonsdale (2004), 17.
\(^{65}\) Lonsdale (2004), 17.
Alexander the Great.\(^{66}\) Cuomo has also applied this theory to the ancient world, in her case with regard to the catapult.\(^{67}\) The catapult fits well into this theory: with its development, the 'passive' tactics of the fifth century (which generally consisted of the circumvallation of the besieged position, possibly alongside attempts to persuade the inhabitants to betray the city or to encourage \textit{stasis}) were replaced with more aggressive tactics.\(^{68}\) Direct assaults on the walls were now less dangerous for attacking forces, since catapults could provide covering shots,\(^{69}\) and as such were made with an increasing frequency throughout the fourth century BC.\(^{70}\) They also represented an advance in defensive technology, since they could be used on the walls of fortifications to hinder an enemy's approach.\(^{71}\) Moreover, catapults were a particularly versatile armament; not only could they be used during siege operations, but they could be deployed as field artillery in a 'set-piece' battle or to provide covering shots if a force needed to cross a river into hostile territory.\(^{72}\) Thus it could certainly be said that they represented a huge advance in military technology and radically changed how engagements were fought.

The great change which catapults brought about for warfare in the Hellenistic period makes their study of particular relevance to our understanding of military history. By examining the practical aspects of their use, we can gain a deeper understanding not only of the effects which they could have on the battlefield, but also of the logistical implications which would have existed for an army with a siege-train. While this latter aspect will not be considered (beyond their portability) as part of this thesis, it is certainly an avenue of research which could be expanded at a later date.

\(^{66}\) Lonsdale (2004), 17.
\(^{67}\) Cuomo (2007), 41ff.
\(^{68}\) Schofield (2009), 7 and 17.
\(^{69}\) Schofield (2009), 19-20, 28-30, and 32-33.
\(^{70}\) Schofield (2009), 28-30, 40-44, 49-50, and 52-54.
\(^{71}\) E.g. at Perinthus – Diodorus Siculus, XVI.74.4-5 (where catapults for defence are loaned to the city by Byzantium), and Halicarnassus – see Arrian, \textit{The Campaigns of Alexander} 1.22, Diodorus Siculus, XVII.24.6 and 26.6.
\(^{72}\) For example in an ambush by Onomarchus – Polyaenus, \textit{Strat.} 2.38.2, and by Alexander when crossing the Tanais – Arrian, \textit{The Campaigns of Alexander} 4.4. See also Rihll (2007), 60.
Scholarly Context

The scholarly context into which this thesis fits must also be considered. First, the way in which this research fits into the field of experimental archaeology will be discussed, followed by how this thesis fits into the more text-based research. The gaps in the research which has been done until now will be highlighted, and in particular it will be noted that Hellenistic catapult technology has been neglected by experimental archaeologists. In more traditional fields of research, scholars have struggled to apply the results of experimentation to the historians' writings.

Some of the early work in experimental archaeology appears to modern eyes not to have been of the highest academic standard. Payne-Gallwey, for example, who wrote in the late nineteenth century, fails to cite as evidence any ancient text when he asserts the sizes he believes appropriate to the components of the onager and ballista. However, in recent years experimental archaeology has had more academically sound principles applied to it. The techniques of reconstructing 'objects, behaviours, and processes' have become more widely recognised as having academic value, with the University of Exeter offering an MA programme in this area. Scholars have also considered the theoretical and scientific principles which form the basis of this field: Mathieu, for instance, offers a 'typology' of the ways in which experimental archaeology is carried out and the different methodologies which each employs, all of which are based on accepted scientific principles.

Two aspects of this typology are particularly relevant to this study: 'Visual Replicas' and 'Functional Replicas'. 'Visual Replicas' are, according to this typology, primarily designed to be handled and used for the purposes of teaching, handling, and display; they

74 As in the title of Mathieu's (2002) work.
75 Cunningham et al. (2008), vi, and http://humanities.exeter.ac.uk/archaeology/postgraduate/taught/maexperimentalarchaeology/ (13/02/14).
may or may not be constructed using 'authentic materials' and processes. 'Functional Replicas' on the other hand are designed specifically 'to be used in a manner similar to the original object'; thus, it is necessary to build the components which cause the object to work using materials which are as authentic and accurate as possible. The catapults reconstructed as part of this thesis fall into the latter category, though their construction should also be of such a standard as to make them visual replicas. As Mathieu points out, however, reconstructions are rarely ends in themselves, and are usually only the starting point for further research. This thesis accepts this principle, and it is the experimentation following the reconstructions which will be the primary focus in proving that replicative experimentation can be as relevant to the study of military history as it is to archaeology, as well as to evaluate the claims made by the ancient historians.

Much of the research which has been carried out to date through experimental archaeology has focused on either material culture or the processes involved in replicating objects. The majority of the work covers the prehistoric period, including the Neolithic period, the Bronze Age, and the early Iron Age, with some research examining the Roman period. In addition, there have been projects on a larger scale, which consider the development of sites, the construction of buildings, and the replication of larger objects. The educational value of experimental archaeology, and the ways in which reconstructions can be used to engage the public have also been considered. In the collections of projects which form the main body of published work concerning the principles of experimental

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78 Mathieu (2002), 2.
81 The studies described in Cunningham et al.'s volume on experimental archaeology demonstrate this well, with five of the six experiments considered being concerned with prehistoric technology and only one concerning Roman technology, along with two articles about the theory of experimental archaeology. See Cunningham et al. (2008). See also Sim and Ridge (2002) for experiments concerning Roman metallurgy and the replication of Roman arms and armour.
82 E.g. Crothers (2008) – the reconstruction of an Anglo-Saxon village; Crumlin-Pedersen (1999) – Viking ship reconstruction; Coles (1973), 55-68 – house reconstructions and destruction, and 97-110 – boat reconstructions from various periods and locations; and the reconstruction of the fifth century BC trireme, Olympias – see Coates and McGrail (1984), Coates et al. (1990), and Morrison et al. (2000).
83 E.g. Crothers (2008), 41-46.
archaeology, military technology tends to have been neglected. Instead, volumes on individual projects have been published, for example the Athenian trireme (the Olympias), or the work of scholars, such as Sim, who reconstructs Roman arms and armour, including (usefully for this thesis) the making of bolt heads for catapult projectiles. Sim has also reconstructed the Dacian falx and tested it for its wounding potential. The Macedonian sarissa has been reconstructed by Connolly and experiments in its practical use by infantry have been carried out. Other reconstructions include Roman military equipment, for example various forms of the pila and a saddle which have been recreated by Connolly. Gladiatorial equipment has been reconstructed by Junkelmann, and Croom has discussed late Roman armour in the context of the problems arising from damage and storage problems for a re-enactment group. The cornu, a musical instrument used in the Roman army, has been reconstructed by Barton. Attempts at the reconstruction of Roman armour are also well documented. A replica of the cover of the Caerleon shield has also been made. Experiential experiments have also been conducted to consider the conditions of marching in the Roman army on those involved and their equipment as well as how the gladius and spatha may be drawn from their sheaths on the right side of the body. Reconstructions of catapults later than those built for this thesis (especially the cheiroballistra) have also been discussed in the academic literature, and the theory of such work has been discussed at length. Many of these

84 Bronze age fighting techniques and weaponry have been considered in the volumes of collected papers, however – see Harding (1999), 87-93, as has neolithic technology – see Shea et al. (2002), 55-62.
85 Coates and McGrail (1984), Coates et al. (1990), and Morrison et al. (2000).
86 Sim and Ridge (2002).
87 Sim and Ridge (2002), 78-84.
89 Connolly (2000b), 107-112.
90 Connolly (2000a), 43-46.
93 Croom (2000), 129-134.
96 van Driel-Murray et al. (1988), 59-64.
98 Morgan (1987), 175.
100 Iriarte (2000), 47-75.
Roman replicas have been published in proceedings of the Roman Military Equipment Conferences. In addition, the *hysplex*, a mechanism used for starting races and which uses torsion technology in a similar way to the catapults, has also been reconstructed successfully.

Previous research on artillery has had its share of problems, and has taken place sporadically. Early research conducted by Payne-Gallwey in the late nineteenth century was, as noted above, academically flawed. The next attempt at catapult reconstruction was made by Schramm in the 1910s. Marsden points out that there were several problems with Schramm's interpretations of the texts, meaning that his stone-thrower had too small an angle of arm movement. Nevertheless, Schramm used horsehair ropes for his springs, which Marsden acknowledges, somewhat grudgingly, as an authentic material. He also tested a number of different catapults for range, as well as his 'two-cubit catapult' for depth of penetration. However, as Marsden notes, the range at which the test of penetration was carried out is not specified by Schramm; moreover, Schramm fails to tell us which of his catapults was used for the range and penetration testing, or whether he was aiming to find the maximum possible range or the longest effective range. This means that his work, too, is somewhat problematic.

Marsden himself carried out reconstruction work in the 1950s and 1960s, and faced technical problems: in his 'three-span catapult' he ultimately substituted rubber for sinew, which he acknowledged was 'much inferior to sinew or hair', and he was forced to construct it 'hastily'. Additionally, in his reconstruction of the *chiroballistra* he had problems in estimating several dimensions which Heron failed to give, including the
thickness of the 'metal parts'.\textsuperscript{111} His work also considered the 'Historical Development' of the catapult, in which he placed the catapult in its historical context.\textsuperscript{112} Additionally, he published the 'Technical Treatises' of Heron, Philon, Biton, and Vitruvius with additional notes and commentary.\textsuperscript{113} Further experimental research on the catapult was carried out in 1971-2 by a team of classicists and engineers at the University of Reading; however, because of 'budget limitations, authentic materials could not be used'.\textsuperscript{114} This limits the usefulness of the study, since there is a greater chance for results to differ from those of a catapult constructed from authentic materials.

Between the 1970s and the early twenty-first century, there was little academic work on catapult reconstruction. In 2002, a BBC documentary followed the (unsuccessful) attempt by Wilkins to build Vitruvius 'one-talent stone-thrower'.\textsuperscript{115} This was beset with problems, including the stretching of the bowstring and shortage of time.\textsuperscript{116} Another documentary, for Channel 5, attempted to reconstruct a Roman bolt-shooting catapult in 2013.\textsuperscript{117} Both documentaries ultimately suffered from the problem that they were attempting a challenge which was too big: both built larger-scale catapults than were commonly used in the ancient world, with teams of workmen who were unused to working on this type of project. Most recently, Watts has reconstructed several catapults, with the data from his experiments gradually being published online.\textsuperscript{118}

The focus of reconstructions has been on Roman catapults, and Greek artillery has only received attention from three scholars of experimental archaeology, who reconstructed the \textit{gastraphetes}. Schramm used a steel bow,\textsuperscript{119} which is inauthentic.\textsuperscript{120} The second was built by Sim, but again the bow (the key component of the \textit{gastraphetes}) was a 'modern'

\textsuperscript{111}Marsden (1999), 232.
\textsuperscript{112}Marsden (1969).
\textsuperscript{113}Marsden (1999).
\textsuperscript{114}Landels (2000), 107.
\textsuperscript{115}'Building the Impossible Episode 2: The Roman War Machine' first broadcast 6/12/2002. See also Wilkins (2003), 57-60 and 76.
\textsuperscript{116}Wilkins (2003), 58-59.
\textsuperscript{117}'Beat the Ancestors Series 1 Episode 2' first broadcast 3/3/2013.
\textsuperscript{118}http://www.wattsunique.com/blog/
\textsuperscript{119}Drachmann (1970), 621. See Fig. 1.
\textsuperscript{120}Marsden (1969), 5 and 8.
one, though the bow was tested for its ease of loading rather than its range.\textsuperscript{121} Stephenson has also built a working \textit{gastraphetes}, although information about its construction materials and methods is unpublished at this time.\textsuperscript{122} Schramm also commissioned replica Greek catapults including Philon's stone-thrower,\textsuperscript{123} wedge-engine,\textsuperscript{124} bronze-spring engine (having steel, rather than bronze, springs),\textsuperscript{125} the repeat-shooting catapult,\textsuperscript{126} and the pneumatic catapult.\textsuperscript{127} These appear to have been small-scale, though Schramm himself does not tell us their exact sizes.\textsuperscript{128}

Additionally, mistakes have been made in the interpretation of the texts; one reconstructed Roman catapult has arms which are too short (the proportion of the spring-diameter to the arms when measured from the supplied photograph is approximately 1:4, when the proportion recommended by Vitruvius is 1:6),\textsuperscript{129} which would certainly have an effect on the ability of the reconstruction to function in the same way as an original catapult. This appears to have been a misunderstanding of the text rather than a textual error (e.g. as a result of a scribe's error when transcribing the manuscript); moreover, Coles, in whose book the photograph appears, has conflated the different types of two-armed torsion engines, citing a formula relevant only to the proportions of the components for stone-throwing catapults in a paragraph in which he describes bolt-throwers, and he clearly refers to 'the arrow' as the missile propelled by the same engine.\textsuperscript{130} His assertion that 'all the calibres [of catapults] were geometrically identical'\textsuperscript{131} is also a complete

\textsuperscript{121}Landels (2000), 227.
\textsuperscript{122}Wilkins (2000), 97 and 101 n. 58 – information for Wilkins' citation of this reconstruction comes only from his private correspondence with Stephenson.
\textsuperscript{123}Schramm (1980), 54-57. On his commissioning the catapults, rather than building them himself, see Baatz (1980), iv. See Fig. 2.
\textsuperscript{124}Schramm (1980), 57-59. See Fig. 3.
\textsuperscript{125}Schramm (1980), 59-60. See Fig. 4.
\textsuperscript{126}Schramm (1980), 60-62. See Fig. 5.
\textsuperscript{127}Schramm (1980), 62-66. See Fig 6.
\textsuperscript{128}Schramm (1980), 8.
\textsuperscript{129}Coles (1973), plate 15. For details on the correct proportions for parts of \textit{ballistae} see Vitruvius, \textit{De Architectura}. 10.11.7. Tables of these are available in Marsden (1969), 44-47.
\textsuperscript{130}Coles (1973), 128. See Vitruvius, \textit{De Architectura}. 10.11.1-2 on the difference in calculating the proportions of parts for each type of catapult, and 10.11.3 for the method of calculating the size of the holes in the spring-frame, and see also below.
\textsuperscript{131}Coles (1973), 128. Stone throwing catapults could, in theory, project sharp missiles, too, (see Rihll (2007), 290) but it is clear from the way Coles describes the catapults that he is misunderstanding the differences between the catapults.
misunderstanding of the text; as Vitruvius notes, stone-throwing catapults and bolt-
shooting engines were of different proportions because of their distinct functions: for
sharp-casting catapults, 'all the proportions of these engines are reckoned from the
proposed length of the arrow which that engine ought to release',\textsuperscript{132} while a stone-thower
was constructed 'to the proposed bulk of the weight of the rock which that engine ought to
release'.\textsuperscript{133} Moreover, even among catapults of the same class, Vitruvius notes that there
was variation in design and proportion, saying that 'the calculations of ballistae are varied
and the differences are arranged for the sake of a single effect'.\textsuperscript{134}

The history of the catapult has also been studied from a textual and historical
viewpoint, without the aid of full-scale reconstructions. Scholars such as Rihll, Cuomo,
Pimouguet-Pedarros, and Landels\textsuperscript{135} focus on the place of catapults within the history of
technology as a whole. They, like Marsden, focus on the phases through which the catapult
went in its development, although Cuomo acknowledges the limitations of this approach,
which revolve around the lack of a clear chronology.\textsuperscript{136} Others have examined the catapult
in the context of work on other subjects, particularly in the field of military history\textsuperscript{137}
and the history of fortifications.\textsuperscript{138} These studies are certainly valuable to our understanding of
the history of the catapult, since they help to contextualise the technology and explain how
the catapult connects with other aspects of history. They are also useful in that they re-
evaluate evidence and present new possible interpretations of it.\textsuperscript{139}

However, because they do not make use of functional replicas, these works provide

\begin{thebibliography}{9}
\footnotesize
\bibitem{132}Vitruvius, \textit{De Architectura}. 10.10.1: \textit{omnes proportiones eorum organorum ratiocinantur ex proposita
sagittae longitudine quam id organum mittere debet}. The term 'sharp-casting' used here refers to the type
of catapult referred to elsewhere in this thesis as a 'bolt-shooter'.
\bibitem{133}Vitruvius, \textit{De Architectura}. 10.11.1: \textit{ad propositam magnitudinem ponderis saxi quod id organum mittere
debet}.
\bibitem{134}Vitruvius, \textit{De Architectura}. 10.11.1: \textit{ballistarum...rationes variae sunt et differentes, unius effectus causa
comparatae}.
\bibitem{136}Cuomo (2007), 42. See also above.
(2006), 47-55, 60-61, 71-73, and 79
\bibitem{138}Winter (1971), \textit{passim}, but especially 218-219, 316, and 311.
\bibitem{139}E.g. \textit{IG II²} 1627 B, lines 328-341. See above for Rihll's contribution to the debate over the meanings
of the listed catapult parts.
\end{thebibliography}

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no new information on the operation of the catapults, and are unable to consider with any conviction the accuracy of the ancient writers in their descriptions of the use and effects of artillery in ancient warfare. These studies also leave space for further study of the texts themselves. As will be discussed below in much more detail, analysis of the texts themselves has been limited by the very little work which has been done on the development of Greek technical writing. Modern scholars' commentaries on the treatises are less useful, too, because it is only by following the instructions laid out in the treatises that it is possible to notice where subtle gaps in the descriptions exist. This thesis will also highlight an aspect of Biton's treatise which has not been observed previously, that his work, in forming a chiasmus and not following the developmental approach taken by Heron and Philon, is more literary than practical.
Methodology

These are the two gaps in our knowledge which this thesis will fill: the overall lack of experimental research into the earliest torsion catapults, and the gap in our understanding of whether and to what extent the ancient historians (as opposed to the ancient technical authors) wrote accurately about the operation and capabilities of the same catapults. The aim of this thesis, therefore, is to examine the extent to which both the process of reconstruction and its outcomes – the catapults themselves and the data which can be gathered from them – provide an additional tool for historians in assessing the written historical record concerning a specific period. In order to do this, I shall construct two catapults: an early torsion stone thrower (*Medusa*) and an early torsion bolt thrower (*Clytaemnestra*).

This thesis will examine the time period during which these catapults were in service: torsion catapults which can be considered 'early' date from the second half of the fourth century until at least the mid-third century BC. However, the technical treatises which describe the building of these catapults date from slightly later and reflect some developments in catapult technology which took place after this time. Therefore, the time period which will be explored in this thesis will run from 350BC to 100BC. By using a combination of experimental archaeology and the text-based approach, a number of different experiments will be performed, including the potential range which catapults may achieve, and the possible depth penetration of missiles on different materials over distance.

The results will then be compared to the claims which the ancient historians made about

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140 For more about whom, see Section 1 'The technical treatises and their authors'.
141 For the purposes of this thesis, 'early torsion artillery' is considered to be the 'Mark I' to 'Mark IV' artillery, as defined by Marsden (1969), 16-24 and 43.
142 Marsden (1969), 43. Primary evidence for the periods during which individual catapult types were deployed will be discussed below.
143 This time frame allows for enough data to be gathered from the historians for a meaningful consideration of how well they understood the use and performance of catapults. It does, however, fall after curved arms began to appear in artistic representations of catapults (e.g. the Pergamum relief, which dates to between 197 and 160/159BC – Bohn and Droysen (1885), 40 and 119ff; see also Marsden (1999), 7 and Plate 3, and Rihl (2007), 128-129, and Figure 6.3 page 129).
the operational performance of the same types of catapults. Accurately reconstructed ammunition and materials appropriate to those against which ancient catapults were used will also be tested, to examine claims by the historians about the impact of missiles.\textsuperscript{144}

Naturally, this means that the catapults which are to be reconstructed must be built as accurately as possible; therefore, a very careful scrutiny of the surviving technical treatises on the construction of catapults is essential before any building begins. Fortunately, there are three technical treatises concerning the catapults from this period: Biton,\textsuperscript{145} Heron,\textsuperscript{146} and Philon.\textsuperscript{147} Vitruvius also provides us with information about later catapult designs\textsuperscript{148}. English translations of all of these texts appear in an edition by Marsden;\textsuperscript{149} DeVoto has also translated the texts of Heron and Philon into English.\textsuperscript{150} There are also German editions and translations available.\textsuperscript{151} A Loeb edition of Vitruvius contains parallel Latin and English text.\textsuperscript{152} Some problems exist with the interpretations of some of the individual words and phrases within the technical treatises which these translators have made; these will be considered in detail as they arise. The survival of these treatises, and their stated purpose of aiding artillery construction, means that, with caution applied to problematic parts of the manuscript tradition, it should be possible to build the catapults to a high degree of functional and visual accuracy. Moreover, we have archaeological evidence in the form of the spring-washers (the component part of the catapult from which it is possible to calculate all other dimensions)\textsuperscript{153} which survive from this period and slightly later; these have been found in locations in countries including Spain, Germany, Britain, Greece, France, Tunisia, the Ukraine, Romania, and Iraq, and have a date range

\textsuperscript{144}See below for details of how the missiles were reconstructed.
\textsuperscript{145}Biton, 61.2-64.2. See below.
\textsuperscript{146}Heron, Belopoeica 75.10-119.2. See below.
\textsuperscript{147}Philon, Belopoeica 52.1-72.4. See below.
\textsuperscript{148}Vitruvius, De Architectura. 10.10.10-12. See below.
\textsuperscript{149}Marsden (1999).
\textsuperscript{150}DeVoto (1996).
\textsuperscript{151}Diels and Schramm (1970), and Schöne (1893).
\textsuperscript{152}Granger (2004).
\textsuperscript{153}Philon, Belopoeica 51.15-55.11, and Heron, Belopoeica 113.3-119.2. See also Vitruvius, De Architectura. 10.10.1 and 10.11.2.
from around 260BC to around AD 380.154 The materials used in the reconstructions must also be considered very carefully. As noted above, several previous reconstructions were severely limited by the materials which their builders used. Therefore the wood, metalwork, and especially the materials for the springs must be as close to the originals (in terms of functionality if nothing else) as possible.155

This thesis will have three major components. The first will take the form of an analysis of the technical treatises, considering the manuscript tradition and where the texts may be flawed or inaccurate, and how we may address such problems. The authors themselves will be examined, evidence for their dates assessed, and the audience for which they wrote discussed. The second part will focus on the process of reconstruction, with a description and explanation of the process for each catapult, and why particular decisions were made with regard to the dimensions, materials, and construction processes. The third section will focus on the process of data gathering: the historians and their evidence for the use of the catapults in their real-world applications will be considered, and this data will be used for comparison with the results the reconstructed catapults achieve. The experiments used to ascertain the range, power, penetration, and damage to different materials which the catapults can achieve will then be described. The final part of this section will focus on how the data gathered relates to the historians’ evidence, and the extent to which their descriptions of the catapults (particularly in the context of sieges, though with some examination of battlefield use) reflects the nature of the machines.

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154 A table of surviving washers and their current locations can be found in Rihll (2007), 295-296.
155 The materials for the springs are of particular concern, since it proved impossible (because of time and budget constraints, as well as a paucity of research on the subject) to use sinew or horsehair. See below under 'Ropes' for more detailed discussion.
**Section 1 – The technical treatises and their authors**

**Introduction**

This thesis relies strongly on technical treatises to provide the basic information for the reconstructions of the catapults. Therefore, it is necessary to establish the nature of the works, their intended audiences, and chronology. Moreover, it is important at this stage to examine their content, and to show the extent and nature of the information which they provide. Here we will consider each of the authors (Heron, Philon, Biton, and Vitruvius) and their texts in turn, while more general conclusions as to how they can be used will be drawn at the end of the chapter.

To understand the nature of the texts, however, it is first necessary to establish a framework which sets out what we should expect from a technical treatise. This framework will be constructed using two sets of criteria: first, Thesleff has noted very generic characteristics of technical writing, which cover a wide range of sub-genres within the field of ancient treatises. Second, more specific features may be considered by using a case-study from a technical treatise on a similar subject. By comparing the artillery treatises to this framework, it will be possible to examine the technicality of each text and to draw conclusions as to the character of the information which each provides. Therefore, the framework considered below will begin by setting out generic characteristics which may be considered appropriate for technical treatises, and will then be modified to reflect the subject at hand.

Several sets of properties belonging to Greek technical prose have been identified by Thesleff, based upon what she describes as 'the “scientific style”'. These are:
• 'explicit argumentation'
• 'systematic structure of exposition'
• 'lack of emotional colouring, external ornament, and superfluous elements'
• 'exactness of expression, e.g. consistent terminology'
• 'abstractness of expression, e.g. wide use of abstract nouns'.\textsuperscript{156}

All but the last of these characteristics seem appropriate to the genre of instruction manuals; the last, however, seems far more suited to a philosophical genre than one which is expected to have a practical and physical use. There are certainly limits to the usefulness of such a generic framework: not all treatises may be expected to conform wholly with the characteristics set out within it,\textsuperscript{157} nor would such a framework have as much relevance to those under consideration here as one tailored to the subject of catapult construction. Therefore, this set of criteria must be modified to make it more appropriate to the artillery treatises.

Very little has been written on the genre of Greek technical texts, especially with regard to the ways in which they are constructed and the types of language they employ, and so other early treatises are useful in suggesting characteristic elements for this model. Military handbooks are of particular use in that they consider similar circumstances to the catapult treatises, albeit from a strategic rather than engineering viewpoint. Aeneias Tacticus' \textit{Poliorcetica} is especially relevant as one of the earliest treatises of its kind,\textsuperscript{158} and it is accepted that it was probably intended for practical use,\textsuperscript{159} which makes it a useful case study from which characteristics of the genre may be drawn. Many of the anecdotes which Aeneias uses as \textit{exempla} in his treatise appear to have come either from 'personal

\textsuperscript{156}Thesleff (1966), 89.
\textsuperscript{157}Thesleff (1966), 89.
\textsuperscript{158}Dating from the mid-fourth century BC, possibly the 350s to the 340s: see Whitehead (2003), 8-9 for internal and external dating evidence, and 36 for Aeneias' work as being one of the earliest extant military treatises. See also Hunter and Handford (1927), xviii ff.
\textsuperscript{159}Whitehead (2003), 39-42, and Hunter and Handford (1927), xxxi-xxxiii.
experience' or from first-hand witnesses, giving him a sense of authority which negates the need for him to explain directly why he is qualified to advise his readers. Moreover, the *exempla* which Aeneias provides show the use of 'practical trial and error' learning, in effect experimentation with strategy. He stresses the importance of making use of 'experienced' men (ἐμπείροις) at several points his work. Practical experience and/or experimentation may, therefore, be proposed as characteristics desirable in the catapult treatises. Aeneias' language also indicates that his book is intended for use: he writes in an instructive style, albeit somewhat disorganised, using impersonal verbs and second-and third-person imperatives, along with warning constructions, to direct his readers' actions. These may all be considered characteristic of instructive literature. Hunter and Handford, in their detailed analysis of Aeneias' language note that he 'has few of the virtues

and some of the vices of a conscious literary "style"'; his work focuses more on direct

160 Hunter and Handford (1927), xxvi provides a catalogue of such *exempla*.
163 E.g. Aeneias Tacticus, 1.4, 6.1-6.3, and 16.19-20; the value of using experience is also expressed at 16.2.
164 Hunter and Handford (1927), lxx, and Whitehead (2003), 18-19.
166 Whitehead (2003), 39.
168 For example ὅπως μή ('take care lest') at 24.1.
169 Aeneias also uses phrases with an infinitive construction where an impersonal verb is missing but expected: e.g. 'these must be men who are well disposed to and pleased with the status quo' (εἰς δέ αὐτοῦς εὖ νοῦς τε καὶ τοῖς καθεστηκόσι πράγμασιν ἀρεσκομένους) – Aeneias Tacticus, 1.6; 'of the rest, appoint the strongest in the prime of youth, when they have gathered, as guards and on the wall' (τὸν δὲ λοιπὸν τοὺς ῥωμαλεωτάτους ἡλικίᾳ καὶ νεότητι ἐκλέξαντα ἐπὶ τὰς φυλακὰς καθιστάναι καὶ τὰ τείχη...) – Aeneias Tacticus, 1.8; 'moreover, when they have set out, send out some to find out what they are doing' (ἐπὶ δὲ πράξεως πορευθέντων καὶ πέμπειν τινὰς γνωσομένους) – Aeneias Tacticus, 4.6; and 'next, do not appoint just any gatekeepers, but prudent and shrewd ones' (ἐξεῖται πυλωροὺς καθεστάναι μὴ τοὺς τυχόντας ἀλλά φρονίμους καὶ ἀγχίνους) – Aeneias Tacticus, 5.1. See also Aeneias Tacticus 6.4, 6.5, 6.6, 6.7, 8.1, 10.3, 10.6ff, 10.12ff, 10.23ff, 15.1ff, 15.6ff, 16.12, 16.16, 16.19, 16.21, 18.1, 19.1, 20.2, 20.5, 22.2ff, 22.11ff, 22.24, 23.1ff, 24.17, 24.19, 25.2, 26.1, 26.6, 26.10, 27.2, 27.14, 27.15, 28.1ff, 29.12, 30.1, 31.4-4a, 31.11ff, 31.14, 35.1, and 36.1.
instruction than philosophy or theory.\textsuperscript{170}

By combining the elements drawn from Aeneias Tacticus' \textit{Poliorcetica}, especially its linguistic elements and instructive style, with the characteristics of Greek technical prose which Thesleff has identified, a purely analytical framework for the properties to which the artillery manuals may be compared can be created. Therefore, the framework will consist of the following points drawn from both sources:

- Specific, specialised and consistent technical language.
- Instructive language and phrasing, particularly in the form of impersonal verbs and imperative forms.
- Subject matter systematically set out.
- A lack of unnecessary detail, i.e. no deviation from the main subject matter except to provide appropriate or relevant analogies to help in explanation or description.
- Practical working knowledge of the subject; the author's personal experience of catapult construction is advantageous.
- Provision of instructions for the building of catapults; the more detailed such instructions are, the better.
- For the purposes of this thesis, those treatises which can be shown to have an audience of engineers and catapult builders in mind are considered more valuable than those which do not.

This emphasis on both technicality and practical knowledge of the subject matter reflects the types of partitions noted in the study of modern technical writing, so that it can be possible to consider the 'subject area' and the 'type of engagement' with the text.\textsuperscript{171} By considering these factors, we can assess what the intentions of the authors were with regard

\textsuperscript{170}Hunter and Handford (1927), lxxi. See also Hunter and Handford (1927) xxxvii-lxxxii for their analysis of Aeneias' language and style. See also Whitehead (2003), 38.

\textsuperscript{171}Langslow (2005), 288.
to how the treatises were intended to be used. The type of language used is also an important element, since by establishing this we can tell whether it is intended to be used primarily as a method of advertising the writer's superior knowledge of the subject or whether it is intended to be used by the reader actually to build catapults.\footnote{Langslow (2005), 289 Table 2.}

The audiences for which the treatises were written must, therefore, also be considered; however, as none of the authors gives an outright description his target audience, this must be judged from the content and style of the texts. An important factor in establishing the authors' intended audiences is the level of technical language they use; for example, where an author uses highly technical language which is consistent, with no glossing even of the most specialised words, then we may well expect his readership to be made up of specialists. Where there is a great deal of explanation of technical information, the language is overly simplified, or little technical or theoretical information is supplied, then we may expect a lay audience. These are two extremes on a spectrum of potential audiences; the former would certainly be more desirable in the type of technical treatise to be used in reconstructing ancient catapults as it would provide a greater depth of technical detail. The latter would still be useful, since it would be of use in glossing the more complex technical vocabulary.

Another parallel with the treatises on siege warfare can be found in the illustrations contained in the manuscripts. Like the artillery treatises, as will be discussed in more detail below, the manuscripts containing treatises on siege warfare contain detailed illustrations.\footnote{The exception among the artillery treatises is Vitruvius – see Martines (1999), 95.} A prime example is Apollodorus of Damascus' \textit{Poliorcetica},\footnote{For the most recent edition of which, see Whitehead (2010).} the manuscripts of which contain a number of drawings.\footnote{Blyth (1992), 133.} Lendle suggests that the illustrations are, in effect, copies of images added during the Byzantine period.\footnote{Lendle (1975), 122.} These illustrations, while of great aesthetic value,\footnote{Commare (1999), 79, and Martines (1999), 95.} do little to help the reader follow...
Apollodorus' advice. The machines described within Apollodorus' Poliorcetica are meant to be reproduced, just as the artillery treatises are designed to help their readers construct catapults of their own. However, Blyth goes so far as to argue that 'the illustrations tell us nothing of value that cannot be derived from the text, and sometimes seriously misunderstand it'; Martines notes that in particular problems occur with the positioning and shaping of the engines' wheels in the images. As with the artillery treatises, problems arise with the use of perspective and the attempts by the artists to create three-dimensional images, and as a result the illustrations can appear malformed or inaccurate. In this regard the illustrations here are a close parallel to those within the artillery treatise manuscripts which also lack clarity and understanding of the text. However, Whitehead describes the illustrations, accurately, as 'stylised scribal elaborations of his [Apollodorus'] words', rather than technical drawings. Unlike the images in the artillery treatises, which are labelled in such a way as to make them appear to be copies (albeit distorted) of original, or at least helpful, illustrations, those featured in the manuscripts of Apollodorus' Poliorcetica seem to be just ornaments to the text.

The main three authors, Heron, Philon, and Biton will be considered as far as possible in chronological order. The authors' chronologies are somewhat problematic, and so they do not appear in the sequence we might initially expect. Heron, for example, who we could expect to be the last of the authors, is here placed first; I will argue, like Marsden and Rihll, that his work is actually a republication of an earlier work by Ctesibius. Philon is the second of the authors to be considered, with Biton the third author in this chapter, and the hardest to date. Owing to the problems in dating these technical writers, the first

178Blyth (1992), 133 n. 16.
179Martines (1999), 91 and 93.
180Blyth (1992), 133 n. 16.
181Martines (1999), 96. See, for example, Fig. 24. For more information on the machine found in this illustration, see Lendle (1975), 103-107, Lendle (1981), 346-347, and Whitehead (2010), 45 and 142 Fig. 4.
182Martines (1999), 95. See also Lendle (1975), 122, and below under 'Heron'.
183Whitehead (2010), 27.
184See below under 'Heron'.
185See below.
half of each section will consider the dates at which they wrote and our knowledge of each author; the second will consider the contents of the texts, including an analysis of their styles and the information they provide. A table based on the general characteristics which we ought to expect from a technical treatise, as set out above, will be used at the end of each section for the purposes of comparison. Since Vitruvius' work must be consulted in order to fill gaps left in the texts of the earlier three authors, a fourth and shorter section will consider the usefulness of his work for this study and how it relates to those of Heron, Philon, and Biton.
Heron

Date and Biography

Heron himself has been dated to some time around 'the second half of the first century AD'.\(^{186}\) He is considered by some scholars, such as Cuomo, to be the original author of the *Belopoeica*;\(^ {187}\) however, as suggested by the introduction to this chapter, there is a general movement among scholars, dating from the early twentieth century and continuing into modern scholarship, which argues that the treatise attributed to Heron is, in fact, a republication of a much earlier treatise by Ctesibius.\(^ {188}\) There are several reasons for this, partly revolving around the machines which are described in the work, and partly regarding the style of writing used by the author.\(^ {189}\) The content and style of the treatise will be discussed in more detail below; however, it is well worth giving them some preliminary treatment here to explain why this treatise is considered a republication, and to ascertain the work's date.

The treatise has been attributed to Heron because of its title, Ἡρώνος Κτησιβίου Βελοποιικά,\(^ {190}\) given in the last line of the work.\(^ {191}\) Whether this was added at a later date or was part of the original cannot be assumed with any certainty. The absence of any entry concerning it in the *apparatus criticus* of Marsden's edition, and a complete lack of discussion of it in his commentary, suggests that it is present in all of the surviving manuscripts. Marsden translates the title as "Heron's edition of Ctesibius' *Construction of Artillery*".\(^ {192}\) This translation is certainly reasonable, but is not the only reason to doubt Heron's authorship of the work.

\(^{187}\) E.g. Cuomo (2002), where at no point in the chapter does the author consider or question whether or not Heron is the original writer of the work, and Cuomo (2007), 53. See Schiefsky (2005), 256-260.
\(^{189}\) Marsden (1999), 1-2, and Rihll (2007), 141-142.
\(^{190}\) Heron, *Belopoeica* 119.3.
\(^{191}\) This line may or may not be part of the original text, but its importance here lies in the fact that it shows that the editors of the work at least believed the work to originate from both Heron and Ctesibius. See Marsden (1999), 2.
\(^{192}\) Marsden (1999), 2.
The treatise's basic structure follows the catapult's development from a discussion of why artillery came into being, and traces it from the *gastraphetes* through to the earliest torsion engines and the engines of the original writer's time; the work concludes with a discussion of the mathematical principles of calculating the dimensions of the spring-hole in stone-throwing catapults.\(^{193}\) All of the engines described considerably pre-date those which had been developed by the first century BC, let alone by Heron's date; as Rihll points out none of the 'advances...described by Vitruvius, for example' are found in the treatise.\(^{194}\) Moreover, it has been argued that the engines described by Heron pre-date even those included in Philon's work.\(^{195}\) Heron's work may be seen as less refined than Philon's, because the formula for calculating the spring-hole diameter in a stone-throwing catapult used by Heron is less sophisticated (and, indeed, less accurate) than those recommended by Philon.\(^{196}\) Furthermore, while in his introduction the author may admit that some of the catapults listed are outdated, there is no suggestion that all of the catapults which he will go on to discuss fall into this category.\(^{197}\) It may not necessarily be the case that later works always improve upon earlier ones, nor that they are always cutting-edge. However, the technology described by Heron and the theoretical principles considered at the end to the treatise are certainly less sophisticated than Philon's version; this may, possibly, suggest that the contents of the work are relatively early, even if the work itself was composed later. While this suggestion is based upon supposition, it may have some implications for how seriously we take this as a technical work,\(^{198}\) and these elements of the treatise provide some circumstantial evidence for an early date for the catapults discussed within the work.

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193Discussion on the original reasons for the invention of catapults: Heron, *Belopoeica* W71-75.9; *gastraphetes*: Heron, *Belopoeica* 75.10-81.2; early torsion: Heron, *Belopoeica* 81.3-90.50; contemporary torsion: Heron, *Belopoeica* 91.1-112.6; spring-holes (for both bolt- and stone-throwers): Heron, *Belopoeica* 112.6-119.2.

194Rihll (2007), 142. Advances include, for example, the curved arms used in later bolt-shooting catapults – see Vitruvius, *De Architectura*. 10.10.5-6.


196Contrast Heron, *Belopoeica* 113.5-114.3 and Philon, *Belopoeica* 51.15-52.19. See also Rihll (2007),147, Marsden (1999), 8, and below.

197ὁς μὴ δὴ ίδιος ὑπαρχόντων (which Marsden (1999) translates was 'even perhaps those out of date'): Heron, *Belopoeica* 73.10-11.

198See below.
Alternatively, as will be discussed below, the relative lack of sophistication in Heron's work may be related to the audience for which he is writing. It may be, as will be argued, that his is a lay readership, for which the high level of technicality provided by Philon is unsuited.\(^{199}\) This could, perhaps, undermine the case that because the catapults described by Heron are different from, and perhaps simpler than, those in Philon's work, they must be earlier. Therefore, other factors must be considered when trying to date this work.

The characteristics of Heron and Ctesibius' writing styles have also been used to argue for Ctesibius as the original author of the *Belopoeica*, since its style seems closer to Ctesibius' than to Heron's.\(^{200}\) For example, in the *Belopoeica* no measurements are actually provided, despite being promised, while Heron's treatise on the *cheiroballistra* gives highly detailed measurements for component parts.\(^ {201}\) It has been argued that Ctesibius generally omitted 'specific measurements' from his work, which makes the *Belopoeica* fit more closely with Ctesibius' style.\(^ {202}\) The technical terminology used by Heron/Ctesibius in this treatise is very similar to that of Philon in his *Belopoeica*,\(^ {203}\) which may indicate that the works were written at similar dates, or that one author may have based his work on the other's style. This does not necessarily mean that the treatise by Heron/Ctesibius pre-dates Philon's; it would be just as reasonable to argue that Philon's was the earlier of the two. However, as Rihll points out, by Heron's time at least some of the vocabulary used in the treatise was outdated.\(^ {204}\) Unless Heron is deliberately archaising, this terminology suggests that either Heron is claiming someone else's work as his own, or is a less proficient technical author than we might otherwise suppose. Finally, Rihll has argued that 'Heron subtracts nothing from the work'; even including a claim that he is the first author to write...

\(^{199}\)See below.

\(^{200}\)Marsden (1999), 1, and Rihll (2007), 142.

\(^{201}\)Heron, *Cheiroballistra*: measurements and dimensions are found throughout the entire work. A translation, critical edition, and commentary of this work are included in Marsden (1999).


\(^{203}\)Schiefsky (2005), 262. See also Marsden (1999), 1-2, and Rihll (2007), 142.

\(^{204}\)For example, Rihll notes that the word for trigger in Heron/Ctesibius' *Belopoeica* (78.2-3) is σχαστηρία, but in Heron's *Cheiroballistra* (126.2-3) the word δρακόντιον is used instead: Rihll (2007), 142. The word σχαστηρία continued to be used, however, as a part of the trigger-mechanism (the claw) rather than standing for the whole construction: see also Heron, *Cheiroballistra* 126.2.
on the subject of artillery for a lay audience. Rihll dismisses this claim, attributing it to Ctesibius as the earlier author. However, in the absence of an original text wholly and directly attributed to Ctesibius, we have no way of knowing whether anything has been added to or taken away from the source material of this treatise; any other assertion or argument is made without any direct evidence. Indeed, if the claim that the author is the first to write for a lay audience were made by Heron rather than Ctesibius, the possibility exists that Heron actually removed more complex or theoretical parts of the treatise to make the work more easily understood by his intended readership. A clumsy attempt to edit the text could explain why no measurements are given in the work, although the author promised them in his introduction, and yet a reasonably complex calculation for working out the diameter of the spring-hole and the 'theorem of the two mean proportionals' are left, or added, in. Yet again, it must be understood that there is no evidence within or outside of the text to show the extent to which the work has been edited. However, in view of the circumstantial evidence, and the technical language used, it seems likely that the text is, at least partly, a republication Ctesibius' original treatise.

This, then, presents us with a problem of how to define the author of this work. Marsden, along with many others, simply refers to the author as Heron. Rihll, on the other hand, cites him as 'Ktesibios'. It would be inappropriate to use squared brackets around either of the two authors' names, as neither is one of them pretending to be the other, nor is the work falsely attributed to either: it is rightly attributed to both. Therefore, for the sake of clarity, Heron, as the later of the two to put his hand to the text, will be cited as its author except where it is more accurate to describe the work as belonging to both jointly. In such cases, the form 'Heron/Ctesibius' will be used.

Since it has been established, therefore, that Ctesibius was the original author, his

205Heron, Belopoeica 73.6-74.4. Rihll (2007), 142.
206Rihll (2007), 142.
207See Heron, Belopoeica 73.6-74.4, 112.7-114.7, and 114.8-119.2
208Marsden (1969) and (1999), passim.
date and context must be considered. There has been little debate in recent times over Ctesibius' date, although there has been some discussion of whether or not the Ctesibius whose work is discussed by Philon, Athenaeus Mechanicus, and in Athenaeus' *Deipnosophistae* is the same person as the Ctesibius whom Vitruvius mentions in his *De Architectura*. Marsden observes that the passages in the *Deipnosophistae* contradict each other regarding the date of Ctesibius, which has given rise to the idea that more than one Ctesibius may have existed. He further notes, however, that 'apart from the...passage in Athenaeus, no one in the ancient world knew of more than one Ctesibius, as is clear from Vitruvius'. Athenaeus is known to have misrepresented the works of other authors, either as a result of his own error or his sources, and it seems that he could be doing something similar here. Certainly, it seems likely that if Vitruvius had known of two or three different engineers called Ctesibius, he would have said specifically which of them he meant, unless there were several men of the same name who were so well known in the ancient world as separate individuals that Vitruvius' readers would be expected to tell them apart without explicit guidance from the author. This seems highly unlikely given the contexts in which Vitruvius mentions the name. This leaves us with the problem of which date from the *Deipnosophistae*, if either, is correct. One of the two references in Athenaeus indicates a date for Ctesibius of c. 270BC, since he apparently 'was active under Ptolemy II', while the other appears to suggest that he should be dated to the time of Ptolemy VII Euergetes II, one hundred to one hundred and fifty years later. However, it has been suggested that

211 Vitruvius, *De Architectura*. 1.1.7, and 7.praef.14 and 9.8.2-7. See Kenny (1932), 190.
213 Sharples and Minter (1983), 154 and 156. For the dangers involved in using Athenaeus as a source, see also Gorman and Gorman (2007), 39-41.
214 While Ctesibius is only mentioned briefly at Vitruvius, *De Architectura*. 7.praef.14 and 1.1.7, much more detail is given at 9.8.2-7. The Ctesibius described here is described in relation to his interests in pneumatics, and while no mention is made of any interest in artillery, it should be remembered that Philon discusses Ctesibius' pneumatically operated catapult alongside his water organ: Philon, *Belopoeica* 77.26-78.22. There is, therefore, some indication that these accounts refer to the same Ctesibius.
215 See note 209 above.
at some point in the text's transmission there was a misunderstanding of an abbreviation which would have been part of the original, allowing this difficulty to be resolved. A substantial number of scholars has postulated that the original phrase read ἐπὶ τοῦ ΒΕὐεργέτου, with the B taken as a numeral, thus giving the reading ἐπὶ τοῦ δευτέρου Εὐεργέτου; however, if the B is taken not as a numeral but as an abbreviation of the word βασιλεύς, the phrase would then read ἐπὶ τοῦ βασιλέως Εὐεργέτου, which would date Ctesibius to the time of Ptolemy III Euergetes I. This would mean that Ctesibius lived during the reigns of two consecutive rulers, and that his dates of activity would be between c.270BC and c.222BC. Although this is a somewhat convoluted explanation, it appears to be much more plausible than the suggestion that there were two different engineers of the same name, and brings together the two pieces of evidence from Athenaeus reasonably convincingly. Nevertheless, B as an abbreviation for βασιλεύς does not appear to have been common (it does not, for instance, appear in Allen's work on Greek abbreviations). A simpler explanation is that it may simply be that there is a factual mistake in Athenaeus' text, which was either present at the time it was written, or crept in later. However, the dates given above for Ctesibius are those accepted by this thesis.

Contents

As described above, the Belopoeica consists of a chronological overview of the catapult's development. The introduction to the work presents its raison d'être as being to provide supplementary information on both the history and construction of the catapult to a (relatively) lay audience. The author then continues with an explanation of some of his technical terminology, differentiating between the euthytone and palintone engines, and

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218Marsden (1999), 6-7, Kenney (1932), 191, Drachmann (1948), 1ff, Perrot (1965), 34-37, Schmidt (1899), x.
219Marsden (1999), 6-7. See also Rihll (2007), 147.
220See Allen (1889).
221Heron, Belopoeica 73.6-74.4.
222Heron, Belopoeica 74.5-9. See also Glossary.
defining his use of the term τὸ βέλος.\textsuperscript{223} This would benefit a lay, rather than specialist, audience, and implies that such a readership was not expected to understand precisely the vocabulary used in this context. The final section in the introduction gives a brief explanation of why catapults developed: Heron claims that a linear development from hand-bows occurred, and that as a result of increased power and range being sought by their makers, the bows themselves had to be mechanised.\textsuperscript{224}

The second section of the work deals with descriptions of catapults in the chronological order of their development, though no datable evidence is given. The \textit{gastraphetes} is the first catapult to be considered; its components are described in terms of their shapes with no dimensions provided,\textsuperscript{225} though Heron describes the use of a ratchet system which was both a safety mechanism and a way of delaying the shot.\textsuperscript{226} Torsion catapults are described next; again, Heron lists no measurements for the individual components, although he does explain their shapes. The earliest version of torsion engines is given first,\textsuperscript{227} and later models are then discussed.\textsuperscript{228} Heron goes on to explain how to build a tool, 'the stretcher' (τὸ ἐντονίον), for creating the rope-springs.\textsuperscript{229} The final part of this section considers the material for, and manufacture of, sinew ropes and the bowstring.\textsuperscript{230}

Heron finally discusses the formulae used for calculating the diameter of the spring-holes in torsion catapults, considering first how to find this measurement for a stone-throwing engine\textsuperscript{231} and then for a bolt-shooting catapult.\textsuperscript{232} The method for calculating the size of the spring-hole for a stone-throwing engine is very similar to the method employed by Philon, though simpler and somewhat less accurate, which may strengthen the argument

\begin{itemize}
\item \textsuperscript{223}Heron, \textit{Belopoeica} 74.10-75.2.
\item \textsuperscript{224}Heron, \textit{Belopoeica} 75.3-9.
\item \textsuperscript{225}Heron, \textit{Belopoeica} 75.10-81.2.
\item \textsuperscript{226}Heron, \textit{Belopoeica} 79.6-81.2.
\item \textsuperscript{227}Heron, \textit{Belopoeica} 81.3-90.5.
\item \textsuperscript{228}Heron, \textit{Belopoeica} 91.1-106.5.
\item \textsuperscript{229}Heron, \textit{Belopoeica} 107.1-110.3.
\item \textsuperscript{230}Heron, \textit{Belopoeica} 110.4-112.6.
\item \textsuperscript{231}Heron, \textit{Belopoeica} 113.5-114.7.
\item \textsuperscript{232}Heron, \textit{Belopoeica} 114.4-7.
\end{itemize}
that this treatise is intended for a lay audience;\footnote{233}{See above, and under 'Philon' below. See also Philon, Belopoeica 51.28-52.19.} the method he gives for a bolt-shooter is identical to Philon's.\footnote{234}{Heron, Belopoeica 114.4-7, and Philon, Belopoeica 54.27-55.1. See under 'Philon' below.} Heron ends the treatise with an explanation of how to calculate diameters for spring-holes of catapults of different sizes based on one already constructed.\footnote{235}{Heron, Belopoeica 115.8-119.2.} As Marsden points out, the calculations involved would have been very difficult to conduct 'without logarithmic tables or a slide rule', equipment not available at the time.\footnote{236}{Marsden (1999), 59.} However, the complexity of the formulae and the processes needed to complete the calculations imply that Heron's 'lay' audience would be expected to have some mathematical knowledge, otherwise they would find this section utterly incomprehensible.

**Style**

Before beginning to consider the style of the work in detail, it is worth considering the overall nature of the treatise; the suggestion that it is intended for a lay audience is an important one for our reading of this text, and so it deserves detailed discussion. The author's claim that the treatise is suitable for a lay audience must be examined; it is also worth questioning the level of education in mathematics required by his audience to be able to understand the work.

The ability of a lay, or experienced audience, to understand or use the treatise depends on their level of mathematical skills. Heron's treatise requires the reader to be able to multiply, find cube roots, add, round numbers up or down, and do simple division.\footnote{237}{Heron, Belopoeica 113.5-114.3.} Geometry, involving the construction of rectangles, diagonals, parallel lines, circles, and the segment of a circle, is also required for the construction of the hole-carriers.\footnote{238}{Heron, Belopoeica 94.1-96.5.} Here, Heron's explanation is somewhat simpler than Philon's first method for the same process, since there is no need to divide a circle into eleven parts to find the correct angle, and is
much easier to follow.\textsuperscript{239} In contrast to Heron's description of how to construct the hole-carrier, moreover, Philon's readers would also need to know how to use reasonably complex fractions.\textsuperscript{240} There is a general consensus in recent scholarship that mathematics was probably taught as an abstract or theoretical subject, rather than a practical one, after the elementary stage.\textsuperscript{241} Plato recommended that children at elementary and secondary level be taught geometry, fractions, and lengths.\textsuperscript{242} Beyond the context of formal education, Rihll points out that anyone who had to deal with any form of accounting or taxation in the ancient world would have required a reasonably good grasp of numeracy, including basic addition and subtraction, fractions, and percentages.\textsuperscript{243} This suggests that anyone with a basic level of mathematical education would be able to follow Heron's work at least in part. Interestingly, textbooks for mathematics which served a practical purpose rather than being purely theoretical in nature did exist in the ancient world; more noteworthy still is the fact that some were written by Heron.\textsuperscript{244} Several of these concern geometry,\textsuperscript{245} a mathematical skill which would be highly useful to someone learning how to construct catapults. The fact that Heron wrote textbooks in another genre which could be used as a learning aid further adds strength to the argument that Heron was aiming at an audience of lay people.

Heron's work is mostly descriptive. Throughout his work, he uses letter forms, like the other two authors, to explain the construction of the catapult.\textsuperscript{246} In Biton's treatise, the author states directly that these letters correspond to those labelling illustrations of the catapults themselves,\textsuperscript{247} while Philon refers to an illustration in his work which has no

\textsuperscript{239}Philon, \textit{Belopoeica} 52.20-29, and Marsden (1999), 159-160. See also Section 2 'Building Medusa' below.


\textsuperscript{241}Plato, \textit{Republic} 536d, and \textit{Laws} 819b-d. See also Beck (1964), 209.

\textsuperscript{242}Rihll (1999), 44-50.

\textsuperscript{243}Marou (1956), 178.

\textsuperscript{244}E.g. Heron, \textit{Definationes}, \textit{Geometria}, and \textit{Geodaesia}

\textsuperscript{245}E.g. Heron, \textit{Belopoeica} 75.10-83.11, 86.9-90.2, 91.8-98.5, 99.3-101.6, 104.4-107.13, and 114.11-119.2. See also e.g. Philon, \textit{Belopoeica} 52.30-53.7, 63.15-66.4, 73.2, 75.30-31, and Biton, \textit{Construction of War Machines} 45.3-51.4 and 62.1-67.1.

\textsuperscript{246}E.g. Biton, \textit{Construction of War Machines} 48.1-2, 51.3-4, 64.2-3, and 67.3-4.
corresponding letters in the text. It seems likely that these letters generally corresponded to illustrations, now lost, possibly following a conventional pattern in works of this type. Such illustrations would certainly be useful in providing clarification for the authors' descriptions. Illustrations accompanying Heron's treatise, some with the relevant letters marked on, appear in manuscripts M and P; how similar to any original drawings these may be is impossible to tell. M is a late medieval or early modern group of manuscripts 'which were bound together in the fifteenth or sixteenth century', while P is significantly earlier and dates from the eleventh century, with corrections added by a second hand in the thirteenth century. The surviving illustrations are distorted images of the catapults, which appear to have been drawn with the aim of showing the whole engine in a single image without consideration of scale or perspective. In some illustrations, it is almost impossible to tell what the subject matter is, and some components such as bow arms may be rotated completely. As Hassall notes, multiple conventions are often followed within the same illustration. With a modern eye, it is difficult to tell how useful these drawings would be to the medieval engineer attempting to use them as a basis for his work. Equally, it is impossible to tell whether the illustrators had actually seen catapults themselves or whether they were simply copying earlier images. Given the level of distortion in the images, the latter seems more likely. It is certainly difficult to tell the extent of the copyist's understanding of the text and illustrations; the more distorted images (all of which occur in M) suggest that the copyist was unfamiliar with this type of catapult technology and struggled to make sense of what he was drawing. While some of the

249 Reproduced in Diels and Schramm (1970), M: Bild 5, page 11 (fol. 47v), Bild 8, page 23 (fol. 49v), Bild 11, page 26 (fol. 49), Bild 19, page 41 (fol. 52v), and Bild 21, page 45 (fol. 54); P: Bild 9, page 23 (fol. 74v), Bild 12, page 27 (fol. 74), and Bild 17, page 36 (fol. 76v). See also Schramm (1980), 11 Abb. 1 and 13 Abb. 2.
250 Marsden (1999), 11.
251 Marsden (1999), 12.
253 See Figs. 20-22.
254 See Fig. 20.
256 See in particular Figs. 15, 17, and 19-22.
illustrations do contain the letters indicated by Heron,\textsuperscript{257} the images themselves are too distorted to be of any practical use for the modern catapult builder. The illustrations from P are considerably clearer and give a basic idea of the catapults' layout but cannot be used for any more than a general impression, again because of the multiple and contradictory conventions used in each image.

The letters given by the authors appear to correspond to fixed points on drawn lines, and the passage which perhaps illustrates this best in Heron's work is that in which he explains how to construct a template for the shape of the hole-carrier. Here the letters represent points at the start of lines, beginning with a rectangle represented by the letters $\text{ΑΒΓ Δ}$, with a diagonal line $\text{ΑΓ}$; the description of the construction of the template continues from there.\textsuperscript{258} Illustrations would be all the more useful in Heron's work, given that he supplies no measurements.\textsuperscript{259} The nearest he comes to providing any dimensions for the catapult parts is at the very end of his work, and this consists only of an explanation of how to calculate the diameter of the spring-hole for any given torsion catapult.\textsuperscript{260}

It is, therefore, interesting to consider why Heron decided to include this information, when he gives no other proportional measurements. As can be seen from Heron's account of the development of the calibration formulae for catapults, and from Philon's description of it in his own treatise, the diameter of the spring-hole (calculated either from the weight of the stone or the length of the bolt which the engine shot) was the key dimension by which all of the other components' measurements were calculated.\textsuperscript{261} The question, therefore, concerns why Heron gives this most important of measurements only at the very end of the treatise. There are several possibilities. First, it may be that, as he claims that he was writing for a lay audience, the important part for Heron was not the

\begin{footnotesize}
\textsuperscript{257}These come mainly from M, but also occur in P. See Figs. 15 an 19-22.
\textsuperscript{258}Heron, \textit{Belopoeica} 94.1-96.5. See also below, Section 2 'Building Medusa' for how the template is drawn in practice.
\textsuperscript{259}See above.
\textsuperscript{260}Heron, \textit{Belopoeica} 112.3-119.2. For an explanation of these terms, see Glossary.
\end{footnotesize}
actual means of constructing catapults, but the theory and principles of this techne. His statement of purpose, which sets out at the beginning of the work that he hopes his work will lead to 'tranquillity' or 'calmness' for his readers and their communities through enabling them to have an understanding of catapult technology greater than or equal to their enemies', as well as that his work is intended for non-specialists, would seem to be evidence to the contrary. Measurements would, therefore, be useful for his readers, and in the second part of his introduction he actually promises to provide 'measurements' for the catapults' components.

Another possibility is that Heron, when editing Ctesibius' work, may have added in the section on the calibration formulae, a section of the work which stands out for its relatively high level of technicality; however, the question of why he did not add proportional measurements for the other components is then raised. It may be that the transmitted treatise is more damaged than it appears, although given that the text flows smoothly and the lack of measurements is consistent throughout the treatise, this seems unlikely. The questions, therefore, remain unresolved, and the issue of measurements in this work, as well as the passage in Heron's introduction, must continue to be regarded as problematic.

It has been noted that Heron's technical vocabulary 'is signalled throughout the text by frequent use of the verb καλέω', and that this tends to follow an explanation or discussion of a part of any given catapult. This seems to follow on from Heron's earlier statement of purpose, which sets out at the beginning of the work that he hopes his work will lead to 'tranquillity' or 'calmness' for his readers and their communities through enabling them to have an understanding of catapult technology greater than or equal to their enemies', as well as that his work is intended for non-specialists, would seem to be evidence to the contrary. Measurements would, therefore, be useful for his readers, and in the second part of his introduction he actually promises to provide 'measurements' for the catapults' components. Another possibility is that Heron, when editing Ctesibius' work, may have added in the section on the calibration formulae, a section of the work which stands out for its relatively high level of technicality; however, the question of why he did not add proportional measurements for the other components is then raised. It may be that the transmitted treatise is more damaged than it appears, although given that the text flows smoothly and the lack of measurements is consistent throughout the treatise, this seems unlikely. The questions, therefore, remain unresolved, and the issue of measurements in this work, as well as the passage in Heron's introduction, must continue to be regarded as problematic.

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262τραπαζία: Heron, Belopoeica 72.1. By positioning himself this way, Heron/Ctesibius is behaving very differently to Philon or Biton. His self-positioning is much closer to Aeneias Tacticus' attitude in the Poliorcetica praef.2, that safety for the community comes through being prepared to fight off an enemy decisively. However, a similar sentiment, that catapults provide security, appears in Vitruvius, De Architectura 10.10.1: nunc vero quae ad praesidia periculi et necessitatem salutis sunt inventa, id est scorpionim et ballistarum rationes, quibus symmetriis comparari possint, exponam. Whether this is Ctesibius positioning himself alongside those writers dealing specifically with sieges or Heron is following an already established literary posture is impossible to tell, though both are possible. In either case, the author is clearly stressing the value of his writing for his readers. If the author is attempting to align himself with authors such as Aeneias Tacticus, this positioning makes sense if the writing is being deliberately targeted at a lay readership since it adds a sense of general authority to the work. Similarly, if this is part of an established literary tradition, the work is again imbued with the author's authority since it marks the work's place in this military technical genre.

263Heron, Belopoeica 71.1-73.5.
264Heron, Belopoeica 73.6-74.4.
265μετρο: Heron, Belopoeica 73.6-74.4, specifically 74.3.
266Scheifsky (2005), 257. N.B. this verb is used much less frequently in Heron's Cheiroballistra appearing only at 130.3 and 131.1.
indication that he is writing primarily for non-specialists; why, otherwise, would a technical author need to signpost the name of a component? Such signposting is certainly something we might consider to be instructive language. Moreover, the explanations which he gives for such basic elements of catapult construction such as for the difference between *palintones* and *euthytones*,267 and for what a missile is,268 should be seen as instructive in the same way.

Nevertheless, the terminology used by Heron is, as Schiefsky has noted, highly 'specialized'.269 Some of this is lay vocabulary which has developed its own technical meaning for the purposes of artillery-construction, 'such as χείρ “claw”, τράπεζα “table”, and κλιμάκις “ladder”.270 Other technical language seems to have developed as the technology advanced, and so the names of some components may have reflected their shape or function, such as that of the hole-carrier, περίτρητον (effectively 'the holes around [the spring-hole]').271 Schiefsky provides tables of the specialised language used by Heron.272 His vocabulary remains consistent throughout the treatise;273 this may suggest that while the audience for which he was writing may have been inexpert, the author himself had a firm grasp of the technical terms which were used in his own or an earlier time. To corroborate this, the technical vocabulary used by Philon 'is quite similar to Heron's'.274

Heron also uses other forms of instructive language throughout his work. He frequently uses the impersonal verb δεῖ275 to give directions to his readers. It is worth noting that, as in Philon's work, the other impersonal verb which we might expect to see,
χρή, 276 is entirely absent. This apparent rejection of the verb χρή is interesting, particularly when it is noted that of the three authors only Biton uses it, but not for an instructive purpose. 277 Liddel has suggested that there may be a subtle difference between these two verbs, at least in their use in oratory, in that χρή may be used to refer to 'general rules', while δεῖ may apply to more 'abstract' concepts; he does note, and it is worth emphasising, that such a 'distinction was not absolute.' 278 Moreover, using Demosthenes 51 as an example, Liddel suggests that δεῖ refers to a 'a more disputable and short-term position' than χρή. 279 He also points out that in the context of oratory 'there seems to be no hard-and-fast rule', and that the two verbs were effectively interchangeable. 280 Heron uses δεῖ mainly for general rules, with only two examples referring to abstract concepts. 281 His use of δεῖ is, as will be shown below, very similar to how Philon uses it. Other examples of Heron's instructive language can be seen in his frequent use of third-person imperatives, with ἔστω being the most common. 282 More rarely, he uses second-person imperatives; because of the context of some of the phrases used, on three occasions it is impossible to tell whether the word used is a third-person or second-person imperative. 283 In any case, this indirect

276 'It is necessary'. See the section on Philon below.
277 See below.
279 Liddel (2007), 159.
280 Liddel (2007), 159.
281 Heron, Belopoeica 116.7 and 117.1
282 'Let it/there be' – Heron, Belopoeica 75.10, 75.14, 76.6, 76.9, 76.12, 86.9, 88.9, 89.1, 89.4, 91.11, 114.6, 114.11 (occurring twice), and 117.6. Other third-person singular imperatives include: ἔγκεισθω ('let it lie') – Heron, Belopoeical 76.8; διασχίσθω ('let it be split') – Heron, Belopoeica 76.10; διώσθω ('push') – Heron, Belopoeica 76.12; ἔστω ('let it be') – Heron, Belopoeica 77.1; γεγονέτο ('let it be') – Heron, Belopoeica 77.6; γνωσθω ('imagine') – Heron, Belopoeica 79.8, 99.3, and 99.5; προσκείσθω ('let it be placed') – Heron, Belopoeica 79.10; γράψαι ('let him describe [a figure]') – Heron, Belopoeica 94.5 (note that this could be a third-person singular imperative); ἐκκόψαι ('let him cut out') – Heron, Belopoeica 94.6 and 94.8 (note that this could be a second-person singular imperative); ποιῆσαι ('let him make') – Heron, Belopoeica 96.10 (note that this could be a second-person singular imperative); τῇρίηθω ('let this suffice') – Heron, Belopoeica 104.3; ἔγκεισθω ('let it have') – Heron, Belopoeica 107.3; γεινόμεθα ('imagine') – Heron, Belopoeica 115.6; παρακείσθω ('let them make') – Heron, Belopoeica 115.8; συμπεπληρωθο (let him complete) – Heron, Belopoeica 117.2; παραπληρωθο (let him lay alongside) – Heron, Belopoeica 117.3; καινόθω ('let him move') – Heron, Belopoeica 117.4. Third-person plural imperatives include γεγονέτο ('let there/be them be') – Heron, Belopoeica 88.1; ἐστιν ('let them be') – Heron, Belopoeica 107.5 and 117.1; ἐπεζεύξθωσαν ('let them join') – Heron, Belopoeica 117.3; and ἐκβεβλήσθωσαν ('let them extend [a line]') Heron, Belopoeica 117.3.
283 γράψαι ('describe [a figure]') – Heron, Belopoeica 94.5 (note that this could be a third-person singular imperative); ἐκκόψαι ('cut out') – Heron, Belopoeica 94.6, 94.8 (note that this could be a third-person singular imperative); ποιῆσαι ('make') – Heron, Belopoeica 96.10 (note that this could be a third-person singular imperative); and (undisputed) λάβε (in this context 'find') – Heron, Belopoeica 113.6.
approach to instruction in the text may, perhaps, be connected with his intended lay audience.\footnote{See above.} Heron's tone implies that he may not be expecting his readership to build catapults themselves; rather, he is explaining how a catapult might be constructed by someone already skilled in the art.\footnote{For example, see Heron, \textit{Belopoeica} 89.6-90.2, where Heron describes the use of catapults in the third person.} However, he also uses first-person plurals throughout the treatise, and this may suggest that in part he was attempting to include his readership in the building process.\footnote{ἐμβάλλωμεν ('we place [something] in') – Heron, \textit{Belopoeica} 85.10; ἐξάπτωμεν ('we fasten') – Heron, \textit{Belopoeica} 85.10 and 85.12; ἀποσχάσωμεν ('we release') – Heron, \textit{Belopoeica} 86.7; ἐπιτευξόμεθα ('we shall hit the mark' i.e. 'we shall aim') – Heron, \textit{Belopoeica} 86.7-8; βουλώμεθα ('[whenever] we wish' – present subjunctive) – Heron, \textit{Belopoeica} 107.10; κατακλινοῦμεν ('we shall lay [them] down') – Heron, \textit{Belopoeica} 107.12-13; ἐξάψομεν ('we shall fasten') – Heron, \textit{Belopoeica} 108.1; ἐκλύσομεν ('we shall untie') – Heron, \textit{Belopoeica} 108.5; ἀποδώσομεν ('we shall attach') – Heron, \textit{Belopoeica} 108.6; and ποιήσομεν ('we shall make') – Heron, \textit{Belopoeica} 108.7.} Alternatively, he may be using the third-person plural to refer to himself, indicating that he himself had some practical experience of artillery-construction.

In summary, therefore, the table below sets out how Heron's \textit{Belopoeica} may be analysed in terms of the model set out in the introduction to this section.

\begin{table}[h]
\centering
\begin{tabular}{|l|p{0.8\textwidth}|}
\hline
\textbf{Technical language} & Heron's technical language is specialised and consistent. Nevertheless, much of his vocabulary comes with explanations which seem to be intended for an audience of non-specialists. This means that each component is described clearly and concisely, and in a way which is easy to understand. However, because of the absence of measurements, it is impossible for the reader to gain a general idea of the size or proportions of any of the components. \\
\hline
\textbf{Instructive language} & Instructive language is used throughout Heron's work, with particular preference for the impersonal verb δέι ('it is necessary') and the third-person singular imperative ἔστω ('let it/there be') shown by the author. He also makes use of second-person indicatives. However, much of Heron's work is indirectly instructive, demonstrating how catapults were built to his audience, rather than explaining directly how his readers might construct them themselves. \\
\hline
\textbf{Systematic approach to the text} & The text is set out systematically, moving chronologically from early non-torsion catapults through to early torsion engines, and finally dealing with the latest model of torsion catapult. The treatise ends with a discussion of the mathematical principles for calculating the \\
\hline
\end{tabular}
\end{table}
<table>
<thead>
<tr>
<th>Lack of unnecessary detail</th>
<th>No unnecessary detail is given in Heron's <em>Belopoeica</em>; explanations are given for each technical term used, as is appropriate for a work which aims to be used by a lay audience.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practical working knowledge</td>
<td>Heron possibly gives some indication in the text (by using first-person plural verbs) that he has practical working knowledge of catapult construction. However, the consistency of his technical language, and the systematic layout of his text indicate that he was confident in his specialist knowledge of artillery-building. If the original author of the treatise is actually Ctesibius, then external evidence demonstrates that the author would have had practical working knowledge of catapult construction.</td>
</tr>
<tr>
<td>Instructions for building catapults</td>
<td>Heron provides detailed descriptions of catapult components, and he gives important information as to how the individual parts of any given catapult fit together. However, he provides no measurements, which limits the usefulness of the information he provides.</td>
</tr>
<tr>
<td>Audience of specialists</td>
<td>Heron states that his intended audience is not one of specialists, but one made up of interested persons with little or no previous experience of catapult construction. While the treatise might be of some use to those who already had some expertise because of the illustrations which it might have contained, and for the descriptions which it provided, it seems to have been Heron's primary intention to reach a lay audience.</td>
</tr>
</tbody>
</table>

Heron's work, therefore, does not fit completely with the framework set out in the introduction to this chapter. The instructions given for building catapults, Heron's possible lack of practical working knowledge, and the intended audience of the treatise limit the usefulness of Heron's work for this thesis. However, his technical and instructive language, his systematic approach to the text, and his lack of unnecessary detail are elements which fit well with the framework. Where gaps are present in Heron's work, the treatises of the other two authors may be useful. Moreover, the technical details which he does provide may be used to complement the information contained within the other treatises as well as to supplement gaps in their descriptions.
**Philon**

**Date and Biography**

Philon's work has been dated to around 200BC or just before. This is partly as a consequence of evidence found within the text (for example the engineers whom Philon cites, particularly Ctesibius), along with external evidence in the form of a relief sculpture in the balustrade of the Temple of Athena Polias at Pergamum. This probable date of publication makes it the second of the three treatises chronologically, since, as has been argued, Heron's treatise is in all likelihood a republication of Ctesibius' earlier work. Certainly, Philon's work must post-date Ctesibius', since he refers to Ctesibius twice. Ctesibius' work, the dating of which has been discussed above, is therefore key in ascertaining the date of Philon's work, and provides a *terminus post quem* of around 270BC.

As Marsden points out, we 'have very little direct information about Philon of Byzantium', and most of the information we have is second-hand. An external piece of evidence, however, may help to provide a *terminus ante quem*. The relief sculpture found at Pergamum, dating from between 197 and 160/159BC shows a torsion catapult with a distinctly curved arm visible. This innovation in the design of arrow-throwing catapults, described by Vitruvius in his own treatise, allows the throwing arms a greater angle of movement than straight arms, and, as Marsden notes, it seems highly unlikely that an engineer who wished to demonstrate the efficiency of his designs would neglect such an important development. The fact that Philon, the most technical of the three treatise

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288 Marsden (1999), 7 and Plate 3, Rihll (2007), 128-129, and Fig. 6.3 page 129, and Bohn and Droysen (1885), 40 and 119ff. See also Fig. 13.
289 Philon, *Belopoeica* 67.28ff and 72.24ff.
290 Marsden (1999), 7.
292 Marsden (1999), 7 and Plate 3. See also Rihll (2007), 128-129, and Figure 6.3 page 129. Bohn and Droysen (1885), 40 and 119ff. See also Fig. 13.
293 Vitruvius, *De Architectura* 10.10.5.
294 Marsden (1999), 7.
writers under consideration, \(^295\) fails to recommend curved arms to his reader is an indication either that this change in design was not familiar to him or that this particular modification to catapult design happened after the time of writing. This argument, while somewhat compelling, is without direct evidence. However, if we accept the argument it would provide a possible \textit{terminus ante quem} of 160/159BC.

When the republished text of Ctesibius is examined alongside Philon's treatise, it has been noted its 'phraseology corresponds closely' to Philon's work. Marsden ascribes this to a likelihood that similar technical language was used in Alexandria at the times when Ctesibius and Philon were working there. \(^296\) While the phrases which he cites do resemble each other, \(^297\) they are limited in number and too short to offer proof of a consistently common phraseology. While paraphrasing on Philon's part cannot be completely ruled out, this small level of similarity does not offer sufficient evidence to suggest either that Philon was highly familiar with Ctesibius' treatise or that he was copying it directly. On the whole, the technical language of Philon and Heron/Ctesibius is almost completely consistent. \(^298\) Where differences in the technical language arise, Marsden suggests that these may be due to Philon's possible association with Rhodes and the engineers working on catapult construction there. \(^299\) However, Marsden may be putting more emphasis on this argument than is reasonable. Although there is no direct evidence, it

\(^295\)See below.

\(^296\)Marsden (1999), 8-9 and 157.

\(^297\)Marsden (1999), 8-9 and 157. Examples of close correspondence of phraseology given by Marsden:

- **Heron, Belopoeica** 74.10 and Philon, Belopoeica 51.8 (ὅρος δὲ τῆς βελοποιικῆς ἐστι τὸ μακρὸν ἀποστέλλειν τὸ βέλος and τῆς δὲ βελοποιικῆς ὅρος ἐστι τὸ μακρὸν ἀποστέλλειν τὸ βέλος respectively);
- **Heron, Belopoeica** 113.5ff and Philon, Belopoeica 51.15ff (both passages are too long to cite in full here);
- and **Heron, Belopoeica** 114.8 and Philon, Belopoeica 51.28 (ὅρος δὲ καὶ ἀπὸ μίας δυμάξεως and ἀπὸ δὲ καὶ ἀν’ ἑνὸς ἀριθμοῦ respectively). See also Schiefsky (2005), 262. Philon's alleged association with Rhodes will be discussed in more detail below.


\(^299\)Marsden (1999), 8-9 and 157. Marsden notes two differences of terminology between Heron and Philon: διόστρα (Heron) and χελώνιον (Philon) both mean 'the slider', and though they both use the term ὑπόθεμα for 'counter-plate', context shows that they mean slightly different things (see Heron, Belopoeica 96.6-98.5, and Philon, Belopoeica 53.8-30): Marsden (1999), 9 and 160. Schiefsky provides a more comprehensive catalogue of the differences in the two authors' terminology, but this amounts to a total of six terms: Schiefsky (2005), 262.
may be that the technical language of artillery-construction was still developing and had not yet become wholly fixed, which could account for such differences.

Moreover, Philon's evidence for Ctesibius' designs appears from the phrasing to come from living memory rather than from written sources; for example, in describing how he came to examine the concept of Ctesibius' bronze-spring engine, he tells us that 'the theoretical problem [i.e. the bronze-spring engine] came to us, when the construction had not yet been passed on', which implies that he heard about the research before it had been written down or published. An oral tradition in artillery construction has certainly been postulated, and with good reason. Later on in the Belopoeica, for example, Philon claims to have spoken with 'some of those who observed Ctesibius' work more carefully', which Marsden takes, not unreasonably, to mean that Philon 'was able to talk to people who had worked with that master craftsman.' His sources also seem to have been particularly well informed about Ctesibius' pneumatically powered catapult. All of this suggests that Philon's was writing was not long after Ctesibius, perhaps only a generation or so later. This, if correct, would place Philon's date around 200BC, the date proposed by Marsden and Rihll.

As noted above, Philon is believed to have had links with engineers in Rhodes and Alexandria. Alexandria was well known as a centre of learning, experimentation, and philosophy, and was an ancient centre of engineering. Philon claims that he visited the city. Ctesibius had worked there on his bronze-spring and pneumatic catapults, and

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300 Προσπεσισάντος δὲ καὶ ἤμιν τὸν προβλήματος, τῆς δὲ κατασκευής οὕτω διαδεδομένης: Philon, Belopoeica 67.29-30.
301 Schiefsky (2005), 255.
302 τίνες τῶν περιγράφετον τὸ τοῦ Κτησιβίου τεθεαμένων: Philon, Belopoeica 72.24-25.
303 Marsden (1999), 6. See also his translation for Philon, Belopoeica 72.24-25.
304 Philon, Belopoeica 77.7-78.22. While no single phrase demonstrates that Philon’s sources were well informed on the subject, the level of detail provided by Philon himself on the subject indicates that he had gathered a great deal of information from his sources.
306 See above.
309 So I shall report to you exactly what I ascertained in Alexandria through much striving with craftsmen engaged in such things, and in Rhodes having been known by many engineers' (ιστορήσωμεν οὖν σοι, καθότι καὶ αυτοί παρειλήφαμεν ἐν Ἀλεξάνδρειας συσταθέντες ἐπὶ πλείον τοῖς περὶ τὰ τοιαῦτα
Heron may later have worked there on his own projects. Rhodes, too, was renowned in the ancient world for its technological prowess in many fields, including military engineering. Interestingly, particularly in relation to the suggestion made by Marsden that Philon may have been using vocabulary especially associated with the Rhodian engineers, both Strabo and Philon use the term ὀργανοποιία to describe 'artillery-construction'. Marsden suggests that this term itself may be 'the characteristic Rhodian term' for this activity. However, this word is, in fact, a fairly generic word for 'instrument making' which occurs in very similar forms in several other contexts, and is certainly not definitive proof that Philon had strong links with Rhodes.

Rhodes, however, also had a particularly active military presence in the Mediterranean during Philon's time, and the city held a large quantity of torsion artillery. This arsenal was a long-standing one; in 305-304BC, the defenders at Rhodes had fended off an attempt by Demetrius Poliorcetes to besiege the city by using their own catapults to great effect. During the conflict, the Rhodians managed to capture eleven of Demetrius' artillery engineers, and would almost certainly have attempted to gain further technical knowledge from them. More than eighty years later, the Rhodian arsenal was so well stocked with artillery that Rhodes was able to lend four complete catapults, along with bowstrings and materials to make replacement strings, to Sinope. Over the next two decades, and therefore quite close to the time at which Philon was writing, Rhodes (together with Byzantium, the polis from which Philon originated) undertook to support

καταγινομένοις τεχνίταις, καὶ ἐν Ῥόδῳ γνωσθέντες οὐκ ὀλίγοις ἀρχιτέκτοσι....): Philon, Belopoeica 51.10-11.

310 Philon, Belopoeica 67.29. See also above, and Marsden (1999), 209.
311 Strabo, Geography 14.2.5. See also Marsden (1999), 157, and Schiefsky (2005), 255.
312 Strabo, Geography 14.2.5, and e.g. Philon, Belopoeica 49.3. See also Marsden (1999), 157.
313 Marsden (1999), 157.
314 LSJ, see under ὀργαν-πήκτωρ. See also below.
315 Strabo, Geography 14.2.5. See also Rihll (2007), 148.
316 Diodorus Siculus, 20.84.4-5, 20.86.2-3, and 20.96.3-97.2. See also Rihll (2007), 117-121.
317 Diodorus Siculus, 20.93.5.
318 Polybius, 4.56.1-3. See also Rihll (2007), 148 – see also 109. Rihll notes that the catapults are 'unusually named'; Polybius calls them λιθοφόρος (4.56.3), which the LSJ suggests is a substitution for λιθοβόλος. See LSJ under λιθοφο-έω.
319 Vitruvius, 7. præf.14 and Heron, Aut. 263.1, where Philon is described as originating from Byzantium. See also Marden (1999), 6.
Philon's possible association, then, with these two cities which were renowned for their bodies of craftsmen and engineers who were skilled in the construction of artillery, adds authority to his treatise. The emphasis which Philon places on his links with Alexandria in particular implies that he does so to convey his expertise to his audience; these same connections also make him more credible to modern readers. Moreover, external evidence that Philon came from Byzantium, another city with a strong reputation in the field of artillery, increases the impression that Philon's background afforded him the opportunity to become familiar with catapult technology. Philon further establishes the credibility of his work by claiming the craftsmen and engineers of the same cities as his sources for some of his *exempla*, along with his own observations. This gives the impression that Philon wished his audience to consider his treatise as both a practical and authoritative source for catapult construction, which is strengthened by the detail, technical qualities, and comprehensiveness of the treatise itself.

**Contents**

Philon's *Belopoeica* is the longest of the three works, which in itself is only a section of a much larger work. There appear to have been nine books in Philon's *μηχανική σύνταξις* in all, covering levers, harbour-building, artillery, pneumatics, the

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320Polybius, 16.2.10. See also Rihll (2007), 148-149.
321See above.
322Byzantium had this reputation from the mid-fourth century onwards: e.g. Diodorus Siculus, 16.74.4, where Byzantium has loaned its artillery to Perinthos, which was being besieged by Philip II of Macedonia, and Byzantium was later involved in fighting alongside and against Rhodes and Pergamum: Polybius, 16.2.10. See also Rihll (2007), 84 and 149.
323E.g. Ctesibius – Philon, *Belopoeica* 67.27ff and 77.10ff; Dionysius of Alexandria (who worked in Rhodes) – Philon, *Belopoeica* 73.21ff. See also Philon, *Belopoeica* 51.10-12 for unnamed engineers as sources.
324Rihll (2007), 148-149, and Schiefsky (2005), 260. The section on artillery and the books on siege warfare, the only parts extant in Greek, were published together in a critical edition by Schöne (1893). See also Marsden (1999), 156.
making of automatic machines, preparations for sieges, siegecraft, and stratagems, together with an introduction.\textsuperscript{325} That this is part of a larger work is indicated by Philon's opening address to Ariston (otherwise unknown).\textsuperscript{326} Parallels to this style of treatise can perhaps be seen Aeneias Tacticus' \textit{Poliorcetica}, which appears to have been part of a similarly constructed larger work,\textsuperscript{327} which included sections on \textit{Preparations},\textsuperscript{328} \textit{Procurement},\textsuperscript{329} \textit{Encampments},\textsuperscript{330} \textit{Admonishments},\textsuperscript{331} and \textit{Naval Manoeuvres}.\textsuperscript{332} The fragments tell us that he also produced sections on \textit{Stratagems}\textsuperscript{333} and \textit{Fire Signals}.\textsuperscript{334} A second, later, parallel can be seen in Vitruvius' \textit{De Architectura}, the first nine books of which focus entirely on architecture, while the tenth and final book examines different types of engineering, including catapult construction.

The section of Philon's work which deals with the construction of catapults, the \textit{Belopoieca}, considers several different forms of artillery: stone-throwing and bolt-shooting catapults are described, along with more unusual types, including a bronze-spring engine and a repeat-shooting catapult; the former is a variation on one built by Ctesibius,\textsuperscript{335} and the latter by another engineer, Dionysius of Alexandria.\textsuperscript{336} This section not only provides technical data, including methods for calculating the appropriate size of catapult based on the calibre of missile to be used,\textsuperscript{337} but also considers theoretical aspects of the catapults themselves, particularly focusing on \textit{why} catapults are able to function, and theorising on

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\begin{itemize}
\item \textsuperscript{325}Marsden (1999), 156, and Rihll (2007), 149. On harbour-building as being one of the other books in a larger work, see Philon, \textit{Belopoieca} 49.1-2; for levers, see 61.13-14; for pneumatics, see 77.12-14. The size of the work as a whole is unknown.
\item \textsuperscript{326}Philon, \textit{Belopoieca} 49.1: ‘...and now it is proper to speak, in accordance with the arrangement we made at the beginning for you, about artillery-construction, called engine-construction by some’ (…νῦν δὲ καθήκει λέγειν, καθότι τὴν ἐξ ὀργῆς δύναται ἐπιστημώντα πρὸς σε, περὶ τῶν βελοποιικῶν, ὑπὸ τῶν ὀργανοποιικῶν καλουμένων): Philon, \textit{Belopoieca} 49.2-3. See also 78.23-26.
\item \textsuperscript{327}Whitehead (2003), 13-16.
\item \textsuperscript{328}Παρασκευαστικός: Aeneias Tacticus, 7.4, 8.4, 21.1, and 40.8.
\item \textsuperscript{329}Ποριστική: Aeneias Tacticus, 14.2.
\item \textsuperscript{330}Στρατοπεδευτικός: Aeneias Tacticus, 21.2
\item \textsuperscript{331}Ἄκουσμα: Aeneias Tacticus, 38.5
\item \textsuperscript{332}Περὶ ναυτικῆς τάξεως: Aeneias Tacticus, 40.8.
\item \textsuperscript{333}Aelian, \textit{Tact.} 3.4.
\item \textsuperscript{334}Polybius, 10.44.
\item \textsuperscript{335}Philon, \textit{Belopoieca} 67.28ff.
\item \textsuperscript{336}Philon, \textit{Belopoieca} 73.21ff. Dionysius of Alexandria is not otherwise attested.
\item \textsuperscript{337}Philon, \textit{Belopoieca} 51.15ff and 55.1ff.
\end{itemize}
how catapult technology could be made more efficient, including a section on the properties of bronze, and how and why it could make the bronze-spring engine function.

**Style**

Philon's discussion of such purely theoretical aspects of artillery-construction separates him from the other authors in terms of their approach to the subject. Biton has no theoretical material at all, other than noting that his machines may be scaled up or down. Heron, too, confines himself almost exclusively to a description of the catapults' components; his only excursus from this is his explanation of how to calculate the size of the diameter of a spring-hole for a stone-throwing catapult, and how this may be scaled up or down according to the catapult's calibre. Philon himself offers us only one clue as to the reason for his interest in this aspect of artillery construction, when, at the beginning of the work, he tells us that he wishes to prove that experimentation and practical experience played a greater part in the development of the catapult than 'pure mechanics'. He compares artillery-construction to early architecture, claiming 'that it is not possible for everything to be understood through reasoning and through the methods of pure mechanics, but that much is found through experimentation, is clear from many other things, not least from what is about to be said'. Precisely what he holds against this branch of theory is not stated, but it is interesting that here he uses a type of theory based on practical experience to argue against another (which lacks practical experience). This suggests that his interest in the practical aspects of catapult construction outweighs his

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340Biton, *Construction of War Machines* 67.5-68.1.
341Heron, *Belopoeica* 75.10ff. See also above.
342Heron, *Belopoeica* 112.7-119.2. See also above.
343Philon, *Belopoeica* 50.26-29: ὅτι γὰρ οὐ πάντα ὅπως ὅλον τῷ λόγῳ καὶ ταῖς ἕκ τῶν μηχανικῶν μεθόδοις λαμβάνεσθαι, πολλὰ δὲ καὶ διὰ τῆς πείρας εὑρίσκεται, φανερῶν μὲν καὶ έξ άλλον πλειόνοις ἑστίν, οὐχ ἠκούστα δὲ καὶ ἀπό τοῦ μέλλοντος λέγεσθαι. See also this quotation in its larger context: Philon, *Belopoeica* 50.14-51.7. For comparison, see Heron, *Belopoeica* 72.3-73.5, who is also disdainful of pure theory.
interest in theoretical approaches, and may imply that he is arguing against specific theoretical works, though there is no direct supporting evidence. Philon's attitude towards the workings of the catapults is pragmatic; he accepts that catapult technology was developed through a process of trial and error, and argues that practical experience of catapult construction is as valuable as, if not more important than, theoretical knowledge. This was not particularly unusual in contemporary science and philosophy; personal observation and experimentation are implied and used directly as sources of evidence in pseudo-Aristotle's *Mechanics* and Archimedes' works.

Rihll suggests that despite his interest in the more technical and theoretical aspects of artillery-building, Philon's level of understanding of the mechanical aspects of catapult construction is somewhat limited. She points to a section where Philon criticises other engineers for increasing the size of the spring-holes in the catapults without enlarging the other component parts proportionately, resulting in some engineers having to reinforce the hole-carriers with metal plating. Rihll argues that 'a more scientific mind would have criticized this practice...because it jettisons the principle of catapult-building by formula', as opposed to Philon's more practical viewpoint, that the practice is inherently wrong because it weakens the machine. This further establishes Philon as an engineer who works from the principles of trial and error rather than purely theoretical premises, and does nothing to detract from his technical competence. Moreover, this section demonstrates his own practical experience and again adds authority to his work. Rihll acknowledges that 'Philon's criticism is... consistent with his belief (expressed several times) that theory does

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345 E.g. Philon, *Belopoeica* 49.12-50.13. This attitude is later taken up by Vitruvius, who also stresses the value of his own first-hand knowledge – Vitruvius, 10.11.2: 'therefore, in order that those who are ignorant of geometry may be equipped and lest they be delayed through the need to calculate during the danger of war, I shall set out the boundaries which I know for certain through practice and which were received partly from my teachers...' (itaque ut etiam qui geometrice non noverunt, habeant expeditum, ne in periculo bellico cogitationibus detinentur; quae ipse faciundo certa cognovi quaeque ex parte accepta praeeptoribus, finita exponam...). See also Marsden (1999), 4.  
not outweigh practice, but does not take this far enough. While she is correct that Philon’s thinking is less systematic than we might like, his consideration of the catapult from a functional viewpoint shows that his interest is not just in how and why it works, but also that he wants to ensure that the engines built using his manual should work and not fall apart the moment they are put under stress. Rihll's criticism of Philon's lack of scientific thinking is misplaced, and she misses his point. A catapult which has flaws not only fails to work properly, but can also be dangerous to the operator. This practical and functional viewpoint must surely take priority in a work aimed at a readership of practitioners. This is important, because Philon's attitude here is clearly an indication that it was just this type of audience to which he was directing his treatise.

The level of detail and heightened sophistication achieved within Philon's work also sets him apart from the other authors, and this is a significant point in our understanding of how Philon's work should be read. Heron, as described above, gives no measurements, while Biton, whose work will be discussed in more detail below, provides sets of measurements with advice to his reader to scale them up or down. Philon takes a different line, providing measurements based on relative proportions: in other words, once the measurement for one part (i.e., the diameter of the spring-hole) has been obtained, the measurements of the other parts may be calculated from it. Heron's method for calculating the size of the spring-hole in any stone-throwing catapult is less sophisticated than Philon's version, which provides two much more accurate methods for calculating the size of the spring-hole. He gives a series of examples, showing the diameters of spring-holes for catapults with calibre of ten minae through to three talents. Philon recommends the use of a template (ἀναγραφεύς) as part of the construction process in order to ensure

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349 As was discovered when both reconstructed catapults malfunctioned during testing – see below.
350 Philon, Belopoeica 53.8-53.9. He does, however, deviate from this approach in describing the repeat-shooting catapult and gives a list of dimensions – Philon, Belopoeica 74.5ff.
351 See above. See also Rihll (2007),147, and Marsden (1999), 8.
352 Philon, Belopoeica 51.15-52.19.
accuracy, a method not suggested by either Heron or Biton. This use of a physical object to create components of the correct size and shape indicates once more a practical mindset. True, theoretical principles must be applied in creating the initial template, but the theory is applied rather than standing on its own; this again adds to the Philon's appearance of practicality combined with a high level of technicality.

Moreover, when considering the bronze-spring engine, Philon not only gives a description of its construction, but also provides criticism, explaining its flaws and how they can be corrected. This is not seen in either Heron or Biton, who only describe each engine's construction. Again, the reason for Philon's different approach is unclear; it may simply be that the formulae for calibrating the different catapults had been developed by his time, but not before Biton and Heron/Ctesibius' works were written, which seems unlikely. It may be that he was writing for a wider audience than the others, and so needed to supply details which would allow the users of his treatise to vary the size of their engines. He may simply have had a greater interest in the more technical and theoretical side of engineering than either Heron or Biton. He may even have been drawing on an earlier work which is not extant. Needless to say none of these suggestions has any concrete evidence to support them, and the text itself provides no clue as to which, if any, is correct. Nevertheless, if we accept any or all of these arguments, they would suggest that Philon should be taken more seriously as a technical author than Biton, whose work, as we shall see, demonstrates little technical knowledge. Moreover, Philon’s work should be considered more useful, as a technical manual, than Heron’s, since it provides a much more detailed consideration and description of the engines.

Philon's work does, however, have some features in common with the other authors. He shares with them an interest in the history of catapult technology, though he ignores non-torsion artillery, focussing instead on how and why torsion engines came to be

353 Philon, Belopoeica 52.20-53.7. Philon also mentions the use of models or pre-made forms (ὁ ἐμβολεύς) to help in the shaping of bronze – see Philon, Belopoeica 70.8 and 70.10.
354 Philon, Belopoeica 67.28ff.
355 Philon, Belopoeica 72.24ff.
developed. It has been suggested that by Philon's time non-torsion artillery had been superseded, which could explain this omission. However, as will be discussed in more detail below, this raises the question of why Biton focussed his treatise on various types of the *gastraphetes*. Nevertheless, there are similarities in the way all three of the authors discuss engineers of the past. Philon's reference to these writers is as vague as Heron's to 'the writers before me who wrote numerous treatises on artillery-construction'. Biton's 'name-dropping' of other engineers and their creations is also paralleled in Philon's work, including references to Ctesibius and Dionysius of Alexandria. It is likely that this is simply a standard way in this genre of asserting the authority and knowledge of the writer, by naming presumably well-known and respected engineers as sources.

At no point does Philon state explicitly the purpose of his work or his intentions when writing it. However, his language and phraseology help to reinforce the air of authority which he gives to his work; throughout the treatise, this gives the work the feel of an instruction manual which is meant to be used. In the more instructive passages (i.e. where he details how individual engines are constructed, or how to carry out particular calculations), he uses, like Heron and Biton, the impersonal command δεῖ; χρηστέον is

358 Philon, *Belopoeica* 50.14-15: 'some of the ancients found that the first order and the basic measure of the construction of engines was the diameter of the hole' (τῶν ἀρχάμων τινς ἠμίροσκον στοιχέων ὑπάρχον καὶ ἀρχή καὶ μέτρων τῆς τῶν ὄργανον κατασκευῆς την τοι τρήματον διάμετρον).
359 Heron, *Belopoeica* 73.6: οἱ πρὸ ἡμῶν πλείστας μὲν ἀναγραφὰς περὶ βελοποιικῶν ἐποίησαντο.
360 E.g. Charon of Magnesia and his stone-thrower – Biton, 45.1-45.2; Isidorus of Abydos and his stone thrower – Biton, 48.3-51.4; Posidonius of Macedon and his siege tower – Biton, 52.1-52.2; Damis of Colophon and his *Sambuca* – Biton, 57.1-58.1; and Zopyrus of Tarentum – Biton, 61.1-62.1.
361 See the example of the bronze-spring engine above.
362 Philon, *Belopoeica* 73.21ff.
363 In Pauly, of the engineers mentioned by Biton, and Philon – Charon of Magnesia, Damis of Colophon, Dionysius of Alexandria, Posidonius of Macedon, and Zopyrus of Tarentum have no entries; however, Ctesibius has an entry in Pauly, 2074-2076. Of all those mentioned, only Ctesibius has an entry in the *OCD*: Toomer (2009) 'Ctesibius'. Diels has identified Zopyrus of Tarentum as a Pythagorean philosopher from circa 350BC – Diels (1920), 23; see also Lewis (1999), 160. See also Drachmann (1963), 11, who identifies Isidorus of Abydos as an *nauarchos* under Antiochus, III in 191BC. – an Isidorus is mentioned by Livy, 36.20.5 and 36.33.7, and Drachmann considers this Isidorus to be the same one as mentioned by Biton; he also postulates that Damis of Colophon may have been 'Damios the Colophonian, *nauarchos* of Eunomia II, about 168BC'. A Damios is mentioned by Livy, 44.28.4-5, and it is this Damios to whom Drachmann refers. Biton himself tells us that Posidonius of Macedon was an engineer to Alexander the Great – Biton, 52.1-2. See also Marsden (1969), 13, and Marsden (1999), 5-6, and 78. For further discussion of these engineers, see the section of this chapter which considers Biton.
364 It is necessary – Philon, *Belopoeica* 51.15, 52.5, 52.22, 54.19, 54.26, 55.10, 55.12, 55.17, 55.18, 55.24, 56.10, 57.1, 57.21, 61.32, 65.1, 67.7, 67.18, 67.20, and 68.15. Also used in the infinitive δὲ – Philon,
also used, \(^{365}\) although, as in Heron's work, χρή \(^{366}\) is notably absent from the text. Whether this is a question of personal preference or a standard form of expression in Greek artillery treatises is unclear, but is discussed in more detail above. Additionally, Philon, again like Heron and Biton, uses third-person imperatives frequently, particularly ἔστω. \(^{367}\) There are also instances in the text where δεῖ or χρή might be expected, but are omitted and only an infinitive is given, \(^{368}\) and occasionally he uses second person singular jussive subjunctives \(^{369}\) or second person singular imperatives. \(^{370}\) It is noteworthy that Philon's use of impersonal verbs and third- or second-person imperatives far exceeds his use of the jussive subjunctive; this is not dissimilar to Aeneias Tacticus' style of writing. \(^{371}\) Moreover, as discussed above, Philon's technical vocabulary for the components is similar to that used by Heron, suggesting that these were either standard terms or that they were at least standard to a particular mechanical school, possibly Alexandria. It may even be that Philon copied this style of writing and terminology directly from other technical treatises, though there is no direct evidence for this. If it were the case, however, it might cast doubt on Philon's technical competence, since he could be seen as merely paraphrasing authors

\(^{365}\) 'One must use' – Philon, Belopoeica 62.26

\(^{366}\) 'It is necessary'.

\(^{367}\) 'Let there/it be' – Philon, Belopoeica 52.4, 52.8, 52.12, 52.31, 62.6, 63.16, 63.18, 63.22, 64.3, 64.12, 64.18, 65.6, 65.7, 66.2, 68.20, and 75.30. Other third person singular imperatives used by Philon include νοείσθω ('let it be perceived') – Philon, Belopoeica 63.19; ἔχετο ('let there/it be') – Philon, Belopoeica 63.24, 63.26, and 64.18; λαβέτω ('let take') – Philon, Belopoeica 64.4; ἀπόκληρθο ('let there be left') – Philon, Belopoeica 65.4 and 65.6; ἀνένεγκε ('lead [it] up') – Philon, Belopoeica 65.22; and εἰρήσθω ('let it have been said') – Philon, Belopoeica 72.2 and 73.20. Third person plural imperatives used by him include καλείσθωσαν ('let them be called') – Philon, Belopoeica 65.17; and ἔστωσαν ('let them be') – Philon, Belopoeica 65.20 and 73.2.

\(^{368}\) E.g. Philon, Belopoeica 53.30 – τὸ δὲ πλάτος αὐτοῦ ποιεῖν ἡμισὺ διαμέτρου ('make the width of it [the arm] half of the diameter [1/2D]'), 54.3-4 – τὰ δὲ ἐπιπήγματα τῆς τραπέζης ποιεῖν πλάτος καὶ πάχος ἔχοντα τῆς κλιμακίδος ('Make the framework of the table with the width and thickness of the ladder'), 54.9-10 – τοῖς δὲ σκέλεσιν αὐτῆς πλάτος μὲν διδόναι διαμέτρου τέταρτον μέρος, ὑπὸς δὲ ὄλης διαμέτρου ('Give the side-poles a width of a quarter of a diameter [1/4D], and a height of a whole diameter [1D]'), 54.11, 54.12, 54.16, 54.22, 54.23, 54.25, 54.31, 55.1, 55.2, 55.3, 55.6, 57.31, 57.32, and 67.23-25.

\(^{369}\) E.g. Philon, Belopoeica 53.30 – τὸ δὲ πλάτος αὐτοῦ ποιεῖν ἡμισὺ διαμέτρου ('make the width of it [the arm] half of the diameter [1/2D]'), 54.3-4 – τὰ δὲ ἐπιπήγματα τῆς τραπέζης ποιεῖν πλάτος καὶ πάχος ἔχοντα τῆς κλιμακίδος ('Make the framework of the table with the width and thickness of the ladder'), 54.9-10 – τοῖς δὲ σκέλεσιν αὐτῆς πλάτος μὲν διδόναι διαμέτρου τέταρτον μέρος, ὑπὸς δὲ ὄλης διαμέτρου ('Give the side-poles a width of a quarter of a diameter [1/4D], and a height of a whole diameter [1D]'), 54.11, 54.12, 54.16, 54.22, 54.23, 54.25, 55.1, 55.2, 55.3, 55.6, 57.31, 57.32, and 67.23-25.

\(^{370}\) E.g. Philon, Belopoeica 53.30 – τὸ δὲ πλάτος αὐτοῦ ποιεῖν ἡμισὺ διαμέτρου ('make the width of it [the arm] half of the diameter [1/2D]'), 54.3-4 – τὰ δὲ ἐπιπήγματα τῆς τραπέζης ποιεῖν πλάτος καὶ πάχος ἔχοντα τῆς κλιμακίδος ('Make the framework of the table with the width and thickness of the ladder'), 54.9-10 – τοῖς δὲ σκέλεσιν αὐτῆς πλάτος μὲν διδόναι διαμέτρου τέταρτον μέρος, ὑπὸς δὲ ὄλης διαμέτρου ('Give the side-poles a width of a quarter of a diameter [1/4D], and a height of a whole diameter [1D]'), 54.11, 54.12, 54.16, 54.22, 54.23, 54.25, 55.1, 55.2, 55.3, 55.6, 57.31, 57.32, and 67.23-25.

\(^{371}\) See above.
whose work has not survived. However, given the high levels of detail which he provides
generally, as well as the implication which he gives of his personal involvement in catapult
construction,372 it seems unlikely that his work is just a copy of another author's treatise.
Philon's use of highly technical vocabulary also adds to his sense of authority as a technical
writer, since such specialised terms would be more familiar to a technical than a lay
audience.

While it could be suggested that Philon's technical vocabulary is simply a device to
promote his supposed expertise, his use of technical terms is consistent throughout his
work, which suggests that he does actually have a clear understanding of his subject. This
consistency in technical language is one of the features of technical writing identified by
Thesleff and incorporated into the framework developed in this chapter's introduction.
Philon's technical language is not glossed for the reader's benefit, which Schiefsky sees as
an indication that the work was not meant for a lay readership, and that the audience
should be expected to have a degree of familiarity with the standard technical terms.373 This
seems entirely plausible, and is consistent with the high level of technicality which is
generally present throughout Philon's work. Moreover, it adds authority to his writing,
since the presumption that his readers are familiar with a highly specialised vocabulary
implies that the author, too, is well acquainted with his subject. This in turn implies that his
readership was made up of military engineers.

Finally, at one point in the text Philon implies that he himself took part in building
at least one of the catapults he describes,374 and this hint of personal experience adds to the

372See below, note 335.
373Schiefsky (2005), 261.
374Philon, Belopoeica 70.6-70.12: 'Next, when the plates had been moulded, forged, and received the
measurements already described, so we gave them a gentle curve against a wooden model; and after this
we beat them while they were cold continuously and for a long while, keeping them equally thick and
straight along the edge, level on the plane, and fitting everywhere against the model. After this we placed
them together in pairs, joining the hollow sides opposite each other and filing down the ends to claws and
joining them to each other with tenons' ('εἴτ' ἐγχυθεισῶν καὶ ἐλασθεισῶν τῶν λεπίδων καὶ λαβουσῶν τὰ
dηλωθέντα μέτρα, οὕτω καμπὴν ἐδώκαμεν αὐταῖς πρὸς ἐμβολέα ξύλινον· καὶ μετὰ ταῦτα ἐκροτήσαμεν αὐτὰς συζεύξαντες καὶ τὰ ἄκρα ῥινήσαντες εἰς ὄνυχα καὶ τόρμοις εἰς ἄλληλα συζεύξαντες).
sense of authority which he gives to his work. The practical involvement which Philon
claims to have had strengthens his position when claiming that experience is more valuable
to the engineer than pure theory, by demonstrating that it is a principle on which he was
willing to act. Philon gives us no reason to think that he is less than honest in claiming
hands-on knowledge of his subject, and his treatise has the feel of being written by a
practitioner. However, beyond this we have no conclusive evidence that he was an engineer
in his own right. Nevertheless, this should not make us doubt his claim, but merely treat
it with a degree of caution.

In summary, then, the table below sets out the ways in which Philon's treatise may
be compared to the framework established at the beginning of this chapter, and outlines the
similarities and differences between the actual treatise and the hypothetical model:

**Table 2: Philon's *Belopoeica***

<table>
<thead>
<tr>
<th>Technical language</th>
<th>Philon's language is highly technical; it is consistent, not only within the treatise, but also with that of at least one other extant author within the same genre; and the vocabulary used is specific, describing individual components of each catapult clearly and concisely, using technical terms which appear to have been common in the genre of artillery treatises.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instructive language</td>
<td>Instructive language, particularly in the form of impersonal verbs and imperatives, is used throughout Philon's text; the language used in consistent, with an overall preference for the impersonal verb δεῖ ('it is necessary') and the third-person singular imperative ἔστω ('let it/there be').</td>
</tr>
<tr>
<td>Systematic approach to the text</td>
<td>Philon's text is set out reasonably systematically, beginning with a brief consideration of the history of catapult construction (49.1-51.14), moving on to torsion catapults (51.15-56.15), problems with torsion catapults and how they may be resolved (57.1-58.23), the wedge-engine, with explanations of how and why it works (58.24-67.27), Ctesibius' bronze-spring engine (67.28-73.20), Dionysius of Alexandria's repeat-shooting catapult (73.21-77.6), and Ctesibius' pneumatic catapult (77.7-78.22). This movement between engines built by separate authors at the end of the treatise means that the treatise cannot be considered wholly systematic, but does not detract</td>
</tr>
</tbody>
</table>

375See above, note 341.
from the overall scheme of standard catapults at the beginning of the work and more experimental catapults at the end.

<table>
<thead>
<tr>
<th>Lack of unnecessary detail</th>
<th>Philon's treatise deals only with catapults, and uses few analogies to explain the work (architecture to explain trial and error as a suitable approach to engineering, 50.30-51.7; levers to explain how the catapult arm works, 59.11-59.22; and Celtic and Spanish swords to explain the flexibility of bronze for the bronze-spring engine, 70.35-71.35). These analogies are used appropriately and with relevance to their context; there is no sign of digression.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practical working knowledge</td>
<td>Philon highly recommends the use of experimentation and a trial and error based approach to catapult construction; he couples this with an implication that he himself took part in building an example of one of the catapults which he describes.</td>
</tr>
<tr>
<td>Instructions for building catapults</td>
<td>Instructions for catapult construction are set out clearly and with a great deal of detail, including proportion-based measurements for each component; Philon recommends the use of models and plans in the construction process, so that catapults may be built accurately, and is more precise and accurate than Heron in his formula for calculating the diameter of the spring-hole. Philon also provides more technical detail than either of the other two authors.</td>
</tr>
<tr>
<td>Audience of specialists</td>
<td>The highly technical nature of Philon's style of writing, the consistency with which he uses technical terminology, and the high level of technical detail suggest that he is aiming for a specialist audience; his instructive language implies that he expects his readers to follow the instructions which he gives, and this further indicates that his intended audience is likely to have consisted of engineers and catapult builders.</td>
</tr>
</tbody>
</table>

From this table, it is possible to see that Philon's work fits extremely well with the hypothetical model. In each of the suggested characteristics, the text either meets or exceeds the basic expectations of a technical text (as set out in the analytical model above), and as a result proves itself to be extremely useful in terms of the practical reconstruction of Hellenistic catapults.
Biton

Date and Biography

Biton's is the hardest of the three Greek works to date, although internal evidence from his text means that he can be reliably dated to one of three periods; to which of these he belongs, however, is less easy to judge. In this section I shall argue that it is actually impossible to determine Biton's exact date. This evidence appears in the very first line of the text, in which Biton makes an address to a 'King Attalus'.\(^\text{377}\) There are three possible figures, all kings of Pergamum, to whom this could refer: Attalus I (241-197BC), Attalus II (159-138BC), and Attalus III (138-133BC).\(^\text{378}\) Drachmann believes that it is one of the latter two kings to whom Biton writes, and he uses an emendation of the name of one of the engineers whom Biton cites to justify his argument.\(^\text{379}\) While this emendation is plausible, it is not enough to provide a date for Biton himself, and some of the other engineers cited by Biton may be of some help in this regard. One engineer, Isidorus of Abydos (who, according to Biton, built a stone-throwing *gastraphetes* at Thessalonica),\(^\text{380}\) is perhaps useful to us. Livy mentions two *nauarchs*, who may possibly be the Isidorus and Damis (emended to 'Damios') whom Biton mentions. However, as Marsden points out, the references which Livy makes to Damius and Isidorus make it impossible to establish these individuals' 'home-towns', and so it is problematic simply to assume that the engineers and the *nauarchs* are the same people.\(^\text{381}\) Nevertheless, Rihll argues for this association between the *nauarchs* and the engineers mentioned by Biton, noting that the *gastraphetes*, the only form of catapult described by Biton, is especially appropriate for naval operations, since,

\(^{377}\) ὦ Ἀτταλε βασιλεῦ: Biton, *Construction of War Machines* W43.1


\(^{379}\) I.e. Damis of Colophon becomes Damios of Colophon, who has been dated to circa 168B.C.; according to Drachmann, Damios of Colophon was a 'nauarchos of Eumenes II', Drachmann (1963), 11. A Damios is mentioned by Livy, 44.28.4-5. See also Rihll (2007), 167 and Marsden (1999), 78. For more on the authors cited by Biton, see 'Philon' above.

\(^{380}\) Identified as a 'nauarchos under Antiochus III, in 191B.C.' by Drachmann (1963), 11. An Isidorus is mentioned by Livy, 36.20.5 and 36.33.7. See also Marsden (1999), 78.

\(^{381}\) Marsden (1999), 78.
not being powered by torsion but through tension, the power-source of the catapult would be less affected by the atmospheric conditions of sea-based warfare. As nauarchs, both of these men would be well placed to gain experience and an understanding of the types of catapults used at sea. While this is an attractive suggestion, there is simply not enough evidence to prove that these engineers were the men whom Livy mentioned. We can perhaps say more safely, however, that Isidorus' date must be after 316-315BC because that was the date at which the city of Thessalonica was founded. This, however is not a particularly useful *terminus post quem* since it has already been established by Biton's address to King Attalus that he must be writing after 241BC.

One engineer, Posidonius of Macedonia, is of little help; Biton tells us that he served Alexander the Great. While we do at least have a secure date of the mid- to late-fourth century for him, probably some time in the 330s BC, this too is not particularly useful in establishing a *terminus post quem*. The other engineers mentioned by Biton are also thought to date from the mid-fourth century BC: Diels has associated the Zopyrus of Tarentum referred to by Biton with a Pythagorean philosopher known to have lived prior to 350BC. Marsden has dated Charon of Magnesia to before 332BC, when the Macedonian occupation of Rhodes began, where Biton tells us that Charon's catapult was built. Unfortunately, Marsden gives no supporting evidence for this claim; his argument appears to be entirely supposition. Rihll proposes that Charon of Magnesia may instead have lived in the early second century BC, citing as evidence for this a 'dramatic decline [in Rhodes] from 168 B.C., when the Romans promoted Delos as a free port', like Marsden, however, she gives no concrete evidence for Charon's presence there at that time.

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383Lewis (1999), 160
386Biton, *Construction of War Machines*, 61.2-64.3.
389Marsden (1969), 75. See also Lewis (1999), 160.
This, therefore, means that we have only one wholly secure date internal to the text, several loose, and possibly erroneous, associations between the engineers listed by Biton and men referenced in other texts, and one engineer who has been dated without any obvious evidence. We must therefore take another approach to dating Biton's treatise.

The approach to this problem taken by Lewis and Rihll is to consider the three kings to whom Biton may have been writing, the technological level at the times during which each of them ruled, and the military situations in which each of them was involved. Marsden also took into account the level of technology available at the time when assessing Biton's date. In addition, Lewis has undertaken a linguistic analysis of some of the technical language used by Biton in order to further clarify his date. However, Marsden, Lewis, and Rihll have arrived at three different dates for Biton: Marsden estimated it at c. 240BC, Lewis proposed 156-155BC, and Rihll believed that it was Attalus III to whom Biton was writing, giving Biton a date of 138-133BC. This method of using external evidence to date Biton, then, has so far produced mixed and problematic results. Nevertheless, by using this approach it may be possible to dismiss the arguments of one or more of these scholars and choose between the possible dates for Biton.

Marsden's suggestion that Biton must have been writing for Attalus I originates in his own belief in a purely linear development of the catapult, and that non-torsion catapults were quickly rendered out-of-date by torsion artillery. This argument is problematic. Cuomo has convincingly argued against a linear model, moreover, as both Lewis and Rihll have suggested, the type of catapult to be used in any given engagement depends on the circumstances surrounding the action and the effects desired from the catapult. Even

393Lewis (1999), 163-166.
396Cuomo (2007), 55-56.
Marsden accepts that non-torsion catapults could have still been 'considered useful in certain circumstances – in field campaigns, for instance, where the springs of torsion engines were not so reliable', but only in the third century BC, and not the second. However, this argument is too weak to justify giving Biton a concrete date in the 240s BC.

The case for a date within the second century has its problems, too. As we have already seen, attempting to date Biton by means of the engineers named within his work is problematic. The approach taken by Lewis suffers from similar difficulties. Lewis uses two of the machines described by Biton in his treatise, the *sambuca* and the *dioptre* to identify Biton's date. In the case of the *sambuca* (a type of mechanical scaling ladder), Lewis notes that one of the components is a κοχλίας or 'screw', which Lewis argues 'must have post-dated Archimedes' invention of the screw', giving it a *terminus post quem* of 241-239BC.

Lewis discounts Marsden's theory that the κοχλίας was a roller operating in much the same way as a winch, and cites an illustration in the manuscript as further evidence for a screw system rather than one operated by a winch. Even without considering the implications of trusting a diagram which was made at least one thousand years after the original text was written, Biton's text is vague enough that he could have been describing either a screw or winch system, and it is impossible to tell which he meant. In any case, whether the term κοχλίας here refers to a screw or a winch, a third century date remains a distinct possibility.

Lewis also considers the name of the *sambuca* itself, and notes that the earliest other use of this name for this type of machine is recorded in Polybius' and Plutarch's

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399Lewis (1999), 163.
400Lewis (1999), 163.
401Lewis (1999), 163. See also Marsden (1999), 94.
403Biton, *Construction of War Machines* 58.8-59.2: 'Through these and through the crest of the three-legged stand, let a κοχλίας be inserted, of which the length is 15 feet, and the perimeter 19 dactyls; and at the feet of the κοχλίας let there be a capstan instead of sockets, so that one can turn the κοχλίας in one direction for lengthening and back again for shortening' (καὶ δὲ αὐτῶν καὶ τῆς κορυφῆς τοῦ κιλλίβαντος διώσθω κοχλίας, οὐ τὸ μὲν μῆκος ποδῶν δὲ περίμετρος δακτύλων καὶ κατὰ τὰς βάσεις τοῦ κοχλίου ἀντί τοῦ ἐπιπονίου ἔστω ἐργάτης, ὡς ἐποστρέφειν ἕνν κοχλίαν κατὰ τὰς ἐκτάσεις καὶ πάλιν εἰς τὸ ἐναντίον στρέφειν κατὰ τὰς ἐλαττώσεις).
accounts of the siege of Syracuse in 214BC. He further notes that in Athenaeus' *Deipnosophistae*, it is recorded that Moschus credited Heraclides of Tarentum with the invention of the *sambuca*, and it is alleged that the engine is a Roman machine. Lewis identifies this Heraclides of Tarentum as the architect mentioned by Polybius, who leant politically towards the Romans and was alleged to have attempted to betray Tarentum to them. Lewis once more takes this to mean that a date of c. 214BC should be accepted for the date of the *sambuca*. However, the fact that these are the earliest datable references to this type of machine as a *sambuca* does not preclude the possibility that it may be Biton who is the first to use this particular name for this type of machine; it is equally possible that he may not be the one who uses this term first. Athenaeus gives no indication of whether he believes Moschus or not, and simply reports it to his reader. Moreover, Lewis utterly ignores the fact that in Athenaeus' description of the *sambuca*, Biton is also mentioned, and with greater prominence as he is the first author given when the discussion considers the *sambuca* as a siege-engine rather than a musical instrument. Therefore, the use of the *sambuca* to provide a date for Biton is problematic, and cannot give us a solid *terminus post quem*.

The same is true of the *dioptra*, which Lewis notes was an instrument used firstly in astronomy, and then later in surveying. Lewis argues that Biton's statement that '...I am knowledgeable about the field of surveying' means that Biton was actually using the *dioptra* as a surveying instrument to measure the height of walls. The word for surveying, ὁ διοπτρικός, is an emendation, with τοῦ διοπτίου present in manuscripts M, F, and V, and favoured by Wescher, τοῦ διοπτίου appearing in manuscript P, and τὸ διοπίον

405Athenaeus, *Deipnosophistae* 634b: 'Moschus in the first book of his treatise on Mechanics says that the machine is Roman, and that Heraclides of Tarentum invented its form' (Μόσχος δ’ ἐν πρώτῳ Μηχανικῶν Ῥωμαικὸν εἶναι λέγει τὸ μηχάνημα καὶ Ἡρακλείδην τὸν Ταραντῖνον εὑρεῖν αὐτοῦ τὸ εἶδος). See also Lewis (1999), 164.
406Polybius, 13.4 Lewis (1999), 164.
407Athenaeus, *Deipnosophistae* 634a.
408Lewis (1999), 165.
410Lewis (1999), 165.
suggested by Thévenot; Marsden and Rehm choose τοῦ διοπτρικοῦ as the most appropriate emendation. Nevertheless, Lewis' argument is reasonable, since earlier in the passage Biton refers to the necessity for siege towers to be of a suitable height for the walls which they are attacking. However, Lewis takes this further, and suggests that, because the object of the surveying exercise is to establish the height of the wall, the instrument used would be the more sophisticated version of the dioptra which he suggests developed in the early second century. Nevertheless, he again fails to prove that the instrument in its later form developed only at that time. Moreover, given that, as Lewis acknowledges, the earlier form of the instrument operated like 'the medieval Jacob's staff', there is little reason to suppose that a new and more sophisticated version would be required for the task. Therefore, Lewis' suggestion is not particularly useful for establishing Biton's date.

Lewis has one final argument in his attempt to prove that Biton was writing to Attalus II. He suggests that Biton was writing his treatise because Pergamum was under military threat from an outside force; he posits that the city's torsion catapults may have been neglected and useless, and suggests that their stockpiles of sinew for rope may have run out, noting that sinew is a highly perishable material. From there he suggests that Biton was instructed by Attalus II 'to trawl through the famous library for a design for a non-torsion stone-thrower that did not require... spring materials.' Lewis points to an attack on Pergamum made circa 156BC by Prusias II of Bithynia. Rihll dismisses Lewis' suggestion, however, with two strong reasons for doubting the validity of his argument. Firstly, she notes that in other cities facing a similar situation to the one described by Lewis, the inhabitants solved the problem of lack of sinew quite easily: their women sacrificed their hair to make torsion ropes. While this could be a symbolic gesture on the

411See apparatus criticus in Marsden's edition – Marsden (1999), 70.
412Biton, Construction of War Machines S2.5-7.
413Lewis (1999), 165-166.
414Lewis (1999), 165.
415Lewis (1999), 162. See also Rihll (2007), 165.
416Lewis (1999), 162. See also Rihll (2007), 165.
417Lewis (1999), 166-167, citing Appian, Mith. 3.
418Rihll (2007), 165. See for example Rome – Vegetius, Epitoma Rei Militaris 4.9; Salonae – Caesar, Civil
women's part, human hair was recognised as a material suitable for the construction of spring-ropes. There is also the question of whether the city would allow its catapults to fall into disrepair: the army of Pergamum was active throughout this period, and it seems unlikely that the army would be well prepared for action in the field and leave the city unprotected; Polybius tells us that Attalus I took particular care of his defences. Furthermore, Rihll points out that Lewis fails to consider the construction time that a non-torsion catapult requires, which includes at least one year for the manufacture of the bow itself. It is therefore not possible to date Biton securely to 156-155BC.

Rihll identifies Attalus III as the king to whom Biton was writing because 'he was reputed a bad king but a good student', basing her argument on the suggestion that he would be the 'most suitable recipient for Biton's final piece of advice'. This passage suggests that it is possible to amend the designs of the catapults to make them appropriate to any situation. He also recommends, in line with Heron and Philon, that the builder or engineer should maintain the symmetry of the design when enlarging or reducing the scale of any catapult. Rihll's main suggestion is that, as Attalus III was a noted scholar, he would be someone to whom Biton's work was of interest. However, given the rigour which she put into arguing against the dates put forward by Marsden and Lewis, Rihll's proposal here is fairly weak. Indeed, she seems to have chosen Attalus III only because the evidence for either of the other two kings is also weak. It is impossible to say with any certainty, therefore, to which of the three kings Biton was writing; it is equally impossible to give him a secure date. There are arguments in favour of each of the possible dates, but there are also contrary arguments to be made for

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419 Heron, Belopoeica 112.1-3.
422 Rihll (2007), 166.
424 Biton, Construction of War Machines 67.5-68.1.
425 Rihll (2007), 168. See also Kosmetatou (2003), 165.
each one. There is too little evidence available for Biton, the catapults, and the text itself, for a solid argument to be made for Biton's chronology. Therefore, we must be content with dating him to somewhere in the period 241-133BC and accept that his date cannot be convincingly narrowed down any further.

Contents

Biton's treatise is the shortest of the three Greek works. Nevertheless, for such a short work the treatise provides a relatively broad coverage of siege machinery. Not only does Biton describe four different versions of the gastraphetes, but he also explains how to build a siege tower and, as discussed above, the sambuca.426 Biton attributes the design of each of the machines to different engineers;427 of the devices listed, only two of the catapults are attributed by him to the same person.428 It is unclear whether the treatise is part of a larger work – Biton mentions another book of his, Optics, which has not survived – but the work on the Construction of War Machines appears to be self contained, having its own clear introduction and conclusion.429 There is no reference at the end of the work to anything which might follow it, nor does the introduction give any hint of following a preceding book. Overall, it is unlikely that the treatise is a section of a larger volume.

The treatise, as Lewis and Cuomo have argued, seems to have been lacking in creativeness on Biton's part; both scholars note that the work is a 'compilation' of other engineers' designs, with Biton acting more as an editor than as a technical author.430 At no point in the treatise does Biton refer to a machine of his own creation, and he gives no

426Catapults: Biton, Construction of War Machines 44.7-48.2 (by Charon of Magnesia), 48.3-51.4 (by Isidorus of Abydos), 61.2-64.3 (by Zopyrus of Tarentum), and 65.1-67.4 (also by Zopyrus of Tarentum).
Siege tower: Biton, Construction of War Machines 52.1-56.7 (by Posidonius of Macedon). Sambuca: Biton, Construction of War Machines 57.1-61.1 (by Damis of Colophon).
427Marsden (1969), 13. See also above.
428Both forms of the gastraphetes: see note 422 above.
429Optics: Biton, Construction of War Machines 53.1. See also Marsden (1999), 26. Introduction and conclusion to Biton's work: Biton, Construction of War Machines 43.1-44.6 and 67.5-68.1 respectively.
indication that he has ever attempted to construct one of the machines he describes. While the descriptions of the machines give figures for the dimensions of each component and the materials to be used, and the conclusion explains how machines may be scaled up or down, these are the only elements of practical advice given by the treatise; Biton himself nowhere questions how or why the catapults function, and he displays no interest in practical knowledge of the catapults themselves.

**Style**

The arrangement of the machines within Biton's treatise appears at first glance to be somewhat haphazard, yet a clear pattern emerges upon closer examination. The first and last two machines in the work are catapults: the former are stone-throwers, the latter are bolt-shooters. Sandwiched between them are the two climbing machines, the siege tower and the *sambuca*; effectively, Biton has created a chiasmic structure for his work. The fact that Biton has created such an artificial structure for his work has not previously been noted by scholars studying this treatise. The very literary arrangement of the text raises questions about the nature of Biton's writing, and whether it was intended as a technical work, to be used by engineers and builders, as a work of literature and an exercise in writing in this genre, or as a combination of both. These questions may, to some degree, be answered by considering other aspects of the style of the text.

Like Heron and unlike Philon, Biton does give us an indication of his purpose in composing his treatise at the very start of the work. His intention, he claims, is to describe how to build a stone-throwing catapult, which is interesting because, as discussed above, his work goes on to describe a combination of stone- and bolt-throwing catapults, as well

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431 Biton, *Construction of War Machines* 44.7-68.1. See also Marsden (1969), 3.
432 Biton, *Construction of War Machines* 44.7-48.2 (stone-throwing catapult), 48.3-51.4 (stone-throwing catapult), 61.2-64.3 (bolt-shooting catapult), and 65.1-67.4 (bolt-shooting catapult).
433 Biton, *Construction of War Machines* 52.1-56.7 (siege tower) and 57.1-61.1 (*sambuca*).
434 ‘I have devoted myself to writing about the construction of a stone-throwing engine’ (λιθοβολοῦ ὀργάνου κατασκευὴν ἐπιβέβλημαι γράψαι) – Biton, *Construction of War Machines* 43.1.
as climbing machines. This suggests either that he is unclear about how he plans to structure his work, or that he is deliberately misleading his reader. The next part of the sentence casts some light onto his intentions. Lewis takes his request to his reader ('do not mock me if some engines happen to fall into a category other than this') as a reference to torsion catapults. Rihll, however, takes this to mean the non-catapult machines contained within the treatise, and this seems more plausible given how Biton began his treatise. I would suggest that Rihll's argument should be expanded: when Biton explains his purpose, he talks about a stone-thrower in the singular, rather than the plural, which implies that this request to his reader refers to the rest of the treatise with the exception of one of the two stone-throwers. This affects our reading, because it suggests that Biton uses the remaining machines partly to contextualise the first stone-thrower he describes, while acknowledging that they may be useful for defensive purposes. Moreover, this, along with his earlier request to the reader, suggests that he thinks that the remaining sections of his work might be thought somewhat 'off-topic', and that he may be supplying something his audience would consider unnecessary detail; he seems here to be making an attempt to apologise and to defend his choice of subject matter. I would suggest that this apparent insecurity, whether genuine or stylistic, may imply that Biton is either less experienced in the field of engineering than the other technical authors or that he wishes to appear so. Either way, it implies that the treatise is more literary than practical.

The technical terminology which Biton uses is consistent throughout the work; however, much of the vocabulary which he uses is very basic, simple, and generic. Even 435μὴ σκώψῃς εἰ τινα ἑτέραν αὐτοῦ εἰς | ὑπόθεσιν πίπτοντα τυγχάνει ὄργανα – Biton, Construction of War Machines 44.1. 436 Lewis (1999), 162 437 Rihll (2007), 170. 438 Biton, Construction of War Machines 44.2-3. 439 E.g. κανόν ('beam') – Biton, Construction of War Machines 45.3, 45.5, 45.6, 45.8, 46.1, 46.5, 46.8, 46.9, 47.1, 47.2, 47.4, 47.6, 47.8, 48.1, 49.3, 49.6, 49.7, 49.8, 49.9, 50.1, 50.2, 50.4, 50.8, 50.9, 50.10, 50.11, 51.3, 62.4, 62.6, 62.8, 63.5, 63.8, 63.9, 65.6, 65.9, and 67.1; ὀδοὺς ('pawl') – Biton, Construction of War Machines 46.5 and 46.7; σφενδόνη ('sling') – Biton, Construction of War Machines 47.1, 47.2, 47.4, and 51.3; τοῖχον ('bow') – Biton, Construction of War Machines 47.5, 51.1, 51.2, 62.8, 62.9, 63.1, 63.7, 63.8, 66.1, and 66.4; κόραξ ('hook' or 'tooth') – Biton, Construction of War Machines 50.9, 51.1, and 63.7; λίνευ ('rope') – Biton, Construction of War Machines 51.1, 63.7, 63.8, 64.2, and 66.10; νευρή ('bowstring') – Biton, Construction of War Machines 51.2, 62.10, and 66.2; βάσις ('base') – Biton, Construction of War
some of the more unusual words which he uses are, in fact, diminutive forms of very basic components. \(440\) There are only two items of technical vocabulary which Biton uses which fall outside the pattern of the standard terminology. One of these, the κοχλίας, has already been discussed for its use in the sambuca; however, Biton also uses this particular term elsewhere in his treatise to refer to a ring attached to the sling in a stone-throwing engine\(441\) and to a roller for a windlass.\(442\) This term does not appear in either of the other two treatises. The second unusual term, κιλλίβας, is also absent from the works of Heron and Philon, and refers to a tripod on which a tension-powered catapult rests.\(443\)

Despite the fact that he does make use of some appropriate, low-level technical terminology, the absence of the more highly technical and sophisticated vocabulary is the most striking feature of Biton's language; the terminology described above is the only technical language which Biton uses. Even some very basic catapult components are ignored, such as the trigger mechanism (one of the most fundamental components), while a complicated ratchet system which prevents untimely release of the missile (which is, in itself, a very useful piece of design) is detailed.\(444\) He also gives no details about the actual operation of the catapult.\(445\) Because Biton fails to consider how the catapults worked, and because he fails to mention such an important component as the trigger mechanism, Biton's style of writing and the contents of his work imply a lack of familiarity with the use and operation of catapults. This itself suggests that he had little or no practical experience of artillery construction and design.

Although Biton uses only a very limited selection of technical vocabulary, his style

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\(^{440}\) Machines 62.2, 62.3, and 65.3; κυτυκλίας ('pawl' or 'bracket') – Biton, Construction of War Machines 62.8 and 65.10; ὠπή ('aperture') – Biton, Construction of War Machines 62.9 and 66.1; ὀξον ('axle') – Biton, Construction of War Machines 64.1 and 66.9; and στῦλος ('pillar') – Biton, Construction of War Machines 66.5.

\(^{441}\) Biton, Construction of War Machines 47.7; σωλήνιδος ('little groove') – Biton, Construction of War Machines 46.3.

\(^{442}\) Biton, Construction of War Machines 47.4.

\(^{443}\) Biton, Construction of War Machines 49.9, 50.2, 50.5, and 51.2.

\(^{444}\) Biton, Construction of War Machines 62.3, 62.5, 64.1, 65.4, 65.9, and 66.9.

\(^{445}\) Biton, Construction of War Machines 45.8-47.1, 50.1-51.4, and 63.9-64.3. This design is confirmed by Heron's description of a similar system – Heron, Belopoeica 79.6-81.2.

\(^{445}\) Contrast, e.g. Heron, Belopoeica 78.4-81.1.
is, nevertheless, instructive. Although, unlike Heron and Philon, Biton makes no use of impersonal verbs when he describing the construction of catapults, he uses third-person imperatives much in the same way as Philon and Heron. Like them, Biton has a distinct preference for forms of εἰμί, especially third person imperatives. He also uses third person indicatives, often in combination with participles, and participles on their own, in such a way as to provide indirect instruction. He uses second person imperatives only twice in the sections on catapults, and the jussive subjunctive only once. This may be connected with Biton's stated target audience: while Heron and Philon seem to have been directing their works at engineers who were, in all likelihood, at the same social level as them, Biton's work is addressed to a king, possibly his patron. Alternatively, it could be that Biton, if he were as unfamiliar with the practical side of catapult technology as he appears, chooses these verb forms as a means of suggestion rather than direct instruction.

446 See above.
447 Although he does so to keep his work moving, e.g. χρή (‘it is necessary’) – Biton, *Construction of War Machines* 53.2: 'But now it is necessary that we change our explanation to the work at hand' (νῦν δὲ ἐπὶ τὸ ὑποκείμενον ἔργον χρὴ τὴν μετάβασιν τῶν λόγων ποιεῖσθαι).
448 Third person imperatives with participles: e.g. ἔστωσαν, especially in combination with ἔχοντες or ἔχον (the phrase as a whole meaning 'let them have') – Biton, *Construction of War Machines* 45.3, 45.8, 45.9, and 46.4-5; also ἔστω in combination with διομένου (the phrase as a whole meaning 'let it be driven through') – Biton, *Construction of War Machines* 50.6. Third person imperatives on their own (active): e.g. ἔστωσαν (let them/there be') – Biton, *Construction of War Machines* 46.1, 46.2, 46.6, 46.9, 63.7, and 65.8; ἔστω (‘let it/there be’) – Biton, *Construction of War Machines* 46.10, 47.1, 47.2, 47.3, 47.5, 49.6, 50.2, 50.6, 51.3, 61.3, 62.9, 63.1, 63.3, 64.1, 65.9, 66.6, 66.7, and 66.9; ἔστεο (‘let it have’) – Biton, *Construction of War Machines* 47.7 and 62.7; ἔστεον (‘let them have’) – Biton, *Construction of War Machines* 49.10, 50.8, 51.1, and 62.5; ἔστεω (‘let it bear/carry/run’) – Biton, *Construction of War Machines* 50.4; ἔστεον (‘let them bear/carry/run’) – Biton, *Construction of War Machines* 64.2; ἔστασαν (‘let it/there be’) – Biton, *Construction of War Machines* 66.5.
449 'I am' from the verb 'to be'. See under ἔστωσαν and ἔστω above, and also ἔστι(ν), ἦν, and ἔσται below.
450 Present: e.g. ἔστι(ν) (‘there is’) – Biton, *Construction of War Machines* 65.3 and 65.5. Imperfect: e.g. ἦν (‘there was’) – Biton, *Construction of War Machines* 49.3, 49.4, 49.6, 49.9, and 62.2; and ἦπισκόπος (‘it used to have’) – Biton, *Construction of War Machines* 49.2, 49.5, 49.10, 62.1 and 62.3. Future: ἔστιν (‘it will be’) – Biton, *Construction of War Machines* 45.6; ὑποθήκησιν (‘we shall place under’) – Biton, *Construction of War Machines* 49.12; and ἥθελος (‘you will place’) – 46.3.
451 E.g. ἔστι, especially in combination with ἔχων (the phrase as a whole meaning ‘it has’) – Biton, *Construction of War Machines* 45.2-3.
452 E.g. συμπεπήγωντος (‘fastened’) – Biton, *Construction of War Machines* 45.5; ἔχοντες (‘having’) – Biton, *Construction of War Machines* 45.5; and ἔγνωκα (‘we shall place under’) – Biton, *Construction of War Machines* 66.5.
453 κάθοδος (‘drop’) – Biton, *Construction of War Machines* 66.1; and παρὰ (‘try’) – Biton, *Construction of War Machines* 67.8.
454 μη παραταραχθῆς (‘do not be troubled’): Biton, *Construction of War Machines* 67.6.
455 See above.
command. Nevertheless, his heavy use of third-person imperatives is similar enough to the style which Heron and Philon employ that it fits reasonably well within the framework of the technical style, even if Biton's tone is less confident than that of the other engineers.

The table below shows how Biton's work compares to the hypothetical model and the extent to which it fits into the suggested framework:

Table 3: Biton's Construction of War Machines

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical language</td>
<td>Biton's vocabulary in this work contains some technical terms, but these are only the most basic and generic. Nevertheless the vocabulary is consistent within the treatise itself, as well as with Heron's work.</td>
</tr>
<tr>
<td>Instructive language</td>
<td>Instructive language in the form of third-person imperatives is used throughout the work with a definite preference for forms of the verb 'to be'; however, no impersonal verbs are used in the technical part of the text, and apart from the third-person imperatives, the instructive language has a tentative quality.</td>
</tr>
<tr>
<td>Systematic approach to the text</td>
<td>The text is set out very systematically, forming a chiasmus in the pattern of two catapults, followed by two climbing machines, followed by two catapults. This very literary formula, however, gives the impression that the treatise is less technical and more literary; therefore, while Biton's approach to the text is systematic, it is systematic in the wrong way for the hypothetical model.</td>
</tr>
<tr>
<td>Lack of unnecessary detail</td>
<td>Given Biton's stated aim (that is, to describe a single catapult and its design) it could be argued that the majority of the work could be considered unnecessary detail. Certainly the parts which deal with the siege tower and the <em>sambuca</em> are superfluous to both the supposed aim of the text and the material needed for this thesis. However, the sections which deal with catapult construction are concise, and so can easily be distinguished from the unnecessary detail found in the centre of the work. Nevertheless, Biton's treatise overall fails to meet this criterion.</td>
</tr>
<tr>
<td>Practical working knowledge</td>
<td>Biton makes no mention of any practical working knowledge on his part. His descriptions are basic, and ignore some of the most basic and necessary components of the catapults (e.g. the trigger mechanism). He does, however, refer to an important safety feature in the form of the ratchet system.</td>
</tr>
<tr>
<td>Instructions for building catapults</td>
<td>Instructions for catapult construction are set out fairly clearly, though with little detail and obvious omissions. Biton gives no direction for the actual building process, although he does provide dimensions for the components (unlike Heron).</td>
</tr>
</tbody>
</table>
Audience of specialists

The low level of detail, the tentative feel to Biton's instructive language, the dedication which Biton gives to King Attalus at the beginning of the work, and his vague instructions at the end of the work on scaling the machines up or down imply that Biton's work would not be useful for an audience of specialists, even if Biton intended his treatise for such a readership. Moreover, the chiasmus formed by the work suggests that this work is more literary in nature, and may well have been intended more as a scholarly exercise in writing a technical treatise than as a working handbook.

Using this model, it is clear that Biton's treatise fits only partially with the framework; overall, I would argue that his work is less useful for the practical reconstruction of catapults than the other treatises. Biton's main redeeming features are that he includes measurements for the catapult components and that he describes an important safety feature in the ratchet system.
There is clearly still some scholarly debate over the dating of Vitruvius' work, although Baldwin notes, in his survey of the current arguments surrounding the date of De Architectura, that, apart from one major outlier whose argument is easily dismissed by internal evidence,\(^{456}\) the general consensus is that the text's publication dates to some point in the last third of the first century BC.\(^{457}\) Marsden and Rihll's arguments for the date of the work's publication fall well within this time period, with an approximate date of 25BC.\(^{458}\) In the preface to Book 1, Vitruvius dedicates his work to Augustus, and lists Julius Caesar and Augustus' sister among his patrons.\(^{459}\) The fact that he mentions a triumph in the first part of his preface seems to indicate that the work must have been published after 29BC.\(^{460}\) A later passage, promising 'immortality' to a number of other writers, including Varro, gives us a slightly later *terminus post quem* of 27BC, since this indicates that the text was published after Varro's death in that year.\(^{461}\) Being dedicated to Augustus, it is clear that it must also have been published prior to Augustus' death in 14AD. However, as Marsden points out, a precise date for Vitruvius, while interesting, is not necessarily of any more use to us than his approximate date as far as his work on artillery is concerned, given that his writing took place at a time when catapult technology was very well established and changes were taking place to the design of artillery more gradually; of more interest is his activity prior to writing his treatise.\(^{462}\)

The preface to the first book of *De Architectura* informs us that along with three other engineers Vitruvius worked on the construction and repair of both bolt- and stone-shooting catapults for Augustus, and notes that he was rewarded by him for good service.\(^{463}\)

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\(^{456}\)Baldwin (1990), 425.  
\(^{457}\)Baldwin (1990), 425-426.  
\(^{459}\)Vitruvius, *De Architectura*. 1.praef.2. See also Marsden (1999), 3, and Baldwin (1990) 429.  
\(^{460}\)Baldwin (1990), 429.  
\(^{461}\)Vitruvius, *De Architectura*. 9.praef.17. See also Baldwin (1990), 429-430.  
\(^{462}\)Marsden (1999), 3.  
\(^{463}\)Vitruvius, *De Architectura*. 1.praef.2: 'And so, along with Marcus Aurelius, Publius Minidius, and
This highlights that Vitruvius was an engineer who understood catapult construction and use in the field, and that he was also concerned with the proper maintenance of artillery. Moreover, the fact that he is explicit about his employment under Augustus means that he is the only one of the technical authors who we can know for certain was both employed as an artillery engineer and was well respected for his ability. This means that, although his catapults date from a period outside the remit of this thesis, his work can be used as supplementary evidence to help in the interpretation of the other texts.

What is particularly striking about the work, given Vitruvius' background, is how little of the work is given over to describing catapults and their design. Only the final book considers machinery at all, and only three chapters discuss artillery.\textsuperscript{464} The overall tone is brisk to the point of being terse. Unlike Heron and Philon, Vitruvius provides no historical contextualisation. Instead, he gives a very brief explanation of the system of proportional measurements for each type of catapult,\textsuperscript{465} and then goes on to give the dimensions for the components.\textsuperscript{466} The final chapter briefly explains how to string and tune catapults.\textsuperscript{467} As the only one of the technical treatises written in Latin, Vitruvius feels the need to gloss some terminology, giving his reader the Greek equivalent terms for some (though not all) of the components.\textsuperscript{468} This indicates that Vitruvius expected his readers to be more familiar with the Greek terminology, and perhaps already to have a reasonable familiarity with catapult technology. This, along with the fact that he crams into a very small part of his broader work all of the information necessary to construct two types of torsion catapult (including the bases, which are ignored by Philon), demonstrates that he is a highly technical author.

\textsuperscript{464}\textit{Vitruvius, De Architectura.} 10.10-12.
\textsuperscript{465}\textit{Vitruvius, De Architectura.} 10.10, 1-2 and 10.11.2.
\textsuperscript{466}\textit{Vitruvius, De Architectura.} 10.10.2-6 and 10.11.2-8.
\textsuperscript{467}\textit{Vitruvius, De Architectura.} 10.12.

\textsuperscript{468}\textit{Vitruvius, De Architectura.} 10.10.3 (\textit{canaliculus} = \textit{syrinx}), 10.10.5 (\textit{posterior minor columna} = \textit{antibasis}), 10.11.4 (\textit{scutula} = \textit{peritretos}), 10.11.7 (parts of the ladder = \textit{chêlê}; \textit{frons transversarius} = \textit{axon}), and 10.12.1 (bronze boxes with pins = \textit{epizygidas}). Where Vitruvius leaves the reader without translations for the Latin vocabulary, his terminology is either easily understood or explained in more detail.
Vitruvius shows no interest in the theory behind how catapults work and, unlike the other technical authors, does not discuss variations on catapult design. He also refuses to give geometrical explanations as Philon and Heron do for the shapes of the hole-carriers in his stone-shooting engine.\footnote{Vitruvius, \textit{De Architectura}. 10.11.2.} This seems to be based on his military experience, since he claims that he reduces his explanations to make the construction of catapults faster and and more straightforward for craftsmen with limited mathematical knowledge during military actions.\footnote{Vitruvius, \textit{De Architectura}. 10.11.2.} His simplified style means that his treatise can be used even by someone who has woodworking experience but relatively little familiarity with geometrical principles, and is, theoretically, of more use to the catapult builder in the field. By giving only the barest, most practical details, Vitruvius makes his treatise useful to the military engineers who need to know how a catapult should be built, without needing (or even, perhaps, wanting) to know the history of the engines or the principles behind their operation. Effectively, the chapters dealing with artillery in this treatise are simply verbal blueprints.

Differences in the construction of the catapults do occur between the time of Philon's catapults and Vitruvius' engines, which mean that Vitruvius' treatise cannot be used entirely as a companion to Philon's work. In the case of the bolt-shooting catapult, the proportions of the spring-frame are different in the two treatises.\footnote{Philon, \textit{Belopoeica} 55.3-9 and Vitruvius, \textit{De Architectura}. 10.10.2. For an easier comparison, see Marsden (1969), 44-45 and Marsden (1999), 266-267, where he gives a table showing the proportions of bolt-shooting catapults according to Philon and Vitruvius side by side.} Moreover, as discussed above, curved arms had been added to the design after Philon's and before Vitruvius' works.\footnote{As demonstrated by the Pergamum relief, see above. See also Vitruvius, \textit{De Architectura}. 10.10.5, Marsden (1969), 43, and Marsden (1999), 270.} In the case of the stone-shooting catapult, the spring-frames are built to a different shape entirely.\footnote{Philon, \textit{Belopoeica} 53.9-17, and Vitruvius, \textit{De Architectura}. 10.11.4-6.} There are enough similarities that Vitruvius may be used to supplement Philon where gaps in his text appear (and where the component does not affect the functioning of the catapult, such as the stand in the case of the bolt-shooting catapult), but not enough for the texts to be interchangeable.
Our three Greek treatises differ from each other in various ways. At one end of the spectrum, Philon writes a highly technical account of catapult construction, explaining the proportional dimensions required for each component. At the other end Biton gives measurements, but shows little technical prowess. His work appears to be more literary than practical, and ignores the theoretical background of artillery construction. Between the two extremes is Heron, whose intended audience appears to be not engineers, but lay people with an interest in the technology; his treatise, correspondingly, is fairly technical, with relatively simple explanations of the components and calculations.

The authors are also distinct from each other in the amount of practical experience which they demonstrate. Philon shows his practical expertise throughout, even going so far as to expound his own design for a new type of catapult using a bronze-spring instead of rope. The level of practical experience shown by Heron comes across more in the tone of the work than through explicit demonstration. External evidence demonstrates that Ctesibius, the original author of the work, had extensive hands-on experience in catapult construction and was a renowned engineer. This implies that any changes to the text by Heron potentially made it less technical and more suited to an audience of non-specialists. Biton, on the other hand, demonstrates no hands-on knowledge of artillery-building.

All three of our authors make use of technical vocabulary and instructive language. Biton is the most hesitant, using only generic terminology and limiting himself to gentle instruction. Philon and Heron, on the other hand, use a much more complex and specific technical vocabulary, along with a combination of imperatives and impersonal verbs to

474Since Vitruvius' work dates from outside of the period under consideration and will only be used as supplementary evidence, only Heron, Philon, and Biton will be discussed in this summary.
475See above.
476For example, in his use of first person plural verbs. See above.
477For Ctesibius' hands-on experience of catapult construction, see Philon, Belopoeica 56.13-15, 67.28-29, 72.24-28, 77.10-12, and 77.29-78.13. For Ctesibius as an engineer, see Vitruvius, De Architectura 1.1.7 and 7.praef.9; for Ctesibius' hands-on experience in other aspects of engineering, see Vitruvius, De Architectura 9.8.2-5.
direct the actions of their readers confidently. This complements the level of technicality which both of these authors show throughout their treatises, in that the level of complexity which they use in describing individual engines and their components is reflected in their use of instructive language.

Heron provides the least amount of superfluous detail in his treatise; every part of his work fulfils his stated purpose. However, he fails to give the detailed measurements of the components, as promised in his introduction.\(^{478}\) Likewise, Philon gives little or no unnecessary detail, and the only analogies which he makes are relevant and to the point. Biton, though, has a large digression in his treatise, concerning the *sambuca* and the siege tower, which is wholly irrelevant to his stated purpose of describing a single catapult.\(^{479}\) Overall, then, Biton's treatise does not match the other two authors in terms of conciseness and relevance. This once again suggests that Biton’s work is not at the same technical level as Philon and Heron's treatises. Moreover, the digression and the descriptions of other catapults which are irrelevant to the author’s stated purpose give Biton the air of a layman trying to impress readers with the range of his knowledge, rather than that of an expert trying to instruct his audience in catapult building. The works by Heron and Philon, then, should be regarded as the more technical and instructive of the three works.

All three authors have, to some degree, a systematic approach to their texts. Heron's is the most straightforward, being a chronological overview of the development of the catapult and its construction. Philon's treatise is slightly less systematic than Heron’s, though overall it follows the same chronological model as his work. However, the end of the treatise is more disjointed than the rest of the work, with the author jumping between catapult designs by different engineers.\(^{480}\) This is problematic, because it makes the end of the work feel more like Biton’s writing, with the author appearing to boast about his wider

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\(^{478}\) See above.  
\(^{479}\) See above.  
knowledge. However, this is understandable in that, having taken a systematic approach to conventional catapults, it seems reasonable to place the more experimental engines in their own section. Moreover, because the catapults differ from each other so much, in terms of their components and sources of power, it is hard to group them into a unified sub-type. While a modern reader might have wished that they at least be classified by inventor, this may have seemed less relevant to Philon than to consider the differing technologies individually. Biton's approach is perhaps slightly more complex, in that it forms a chiasmus beginning and ending with artillery, with other siege equipment discussed in the middle portion; this chiasmus gives the work a very literary feel. Nevertheless, while this may be systematic in the sense that the style of writing follows a strict pattern, it is not set out in an appropriate way for an engineering manual, being overly complicated and unsuited for practical use.

The table below shows the degree to which each of the authors meets the model for technical writing set out in the introduction, based upon the analyses made in each section of this chapter:
Table 4: Meeting the hypothetical model

<table>
<thead>
<tr>
<th></th>
<th>Heron</th>
<th>Philon</th>
<th>Biton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical language</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Instructive language</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Systematic approach to the text</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Lack of unnecessary detail</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Practical working knowledge</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Instructions for building catapults</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Audience of specialists</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

1 = Fully meets the criterion  
2 = Mostly meets the criterion  
3 = Partially meets the criterion  
4 = Fails to meet the criterion

In terms of the model, therefore, Philon is clearly the best fit, with Heron a close second. Biton meets none of the criteria fully, completely failing to fulfil two of them. This indicates that the treatises of Philon and Heron are the most useful for the purposes of this thesis, especially since they both demonstrate high levels of technicality and the potential for the texts to be applied practically. Biton's treatise, on the other hand, has limited use for this thesis; its lack of practical knowledge, technical understanding, and the problems of its style mean that only small portions of the work can be used in the catapult reconstructions. His work appears not to have been written to be used as a practical manual; a modern analogy might be that his is a ‘coffee table book’ in comparison to Philon’s ‘Haynes manual’. The unsuitability of his treatise for this project is further compounded by the fact that at no point in the work is torsion technology discussed. Philon’s work is certainly aimed at the expert reader, while Heron’s treatise is suitable for someone with little previous knowledge of engineering, who might or might not be interested in building his
own piece of artillery.

The extent to which the artillery treatises fulfil the criteria of the model directly affects their usefulness for the practical part of this thesis. Biton can be almost completely ruled out from this section, mainly because he concerns himself only with non-torsion catapults but also because his lack of technicality means that his work has only limited potential for use in the reconstruction of the catapults for this project. However, some parts of his work (such as his advice on choices of wood and the design for the ratchet system) are echoed in the other treatises and can be treated as reasonable suggestions. Heron's work is based much more in the practicality of catapult construction and shows a degree of technicality which is absent from Biton's treatise. Nevertheless, Heron's Belopoeica cannot be used in isolation, since he provides us with no dimensions for the components.

On the other hand, Philon, who is both technical and practical, provides us with the majority of the information needed to reconstruct Hellenistic torsion catapults. There are gaps in his coverage of the material, however, for which Heron can be used. For example, Philon's description how to construct the template for making the hole-carrier is very unclear and lacks some of the detail needed to complete it. However, when this is combined with Heron’s method for the production of the same thing, which also lacks certain necessary information, a working template can be constructed which fits the few measurements provided by Philon. Heron’s treatise, then, is almost as useful as Philon’s because of the gaps which it is able to fill. It must be remembered, however, that the technical vocabulary used by Philon and Heron is not completely identical, nor do components with the same names necessarily map onto each other. As Marsden notes, ‘Philon’s blocks (πλινθίδας) roughly correspond to Heron’s counter-plates (ὑπόθεματα)’,

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481 Wood: Biton, Construction of War Machines 44.5-6, Philon, Belopoeica 62.6 and Heron, Belopoeica 102.5-10. Ratchet system: Biton, Construction of War Machines 45.8-47.1, 50.1-51.4, and 63.9-64.3. and Heron, Belopoeica 79.6-81.2.
482 Philon, Belopoeica 52.20-53.7. See also Section 2 'Building Medusa'.
483 Heron, Belopoeica 94.1-96.5. See also Section 2 'Building Medusa'.
484 For example, both use the term ὑπόθεμα to mean ‘counter-plate’: Heron, Belopoeica 97.7 and Philon Belopoeica 53.16, 54.18, 57.24. See also Marsden (1999), 9, 53, 160, and 164, and Schiefsky (2005), 262.
485 Marsden (1999), 164.
while ‘Philon’s ‘underwasher’ (ὑποχοινικίς) is equivalent to Heron’s ‘counter-plate’ (ὑπόθεμα).

Thus, it will be necessary to exercise caution when using one of the two texts to complement the other to ensure that no confusion arises as a result of their occasionally differing terminology. Vitruvius can be used in a similar capacity, with the caveat that, as an author discussing a later design of catapult, efforts must be made to avoid anachronism and to note where dissimilarities in design could adversely affect the reconstruction of the Hellenistic engines. Therefore, the main text which will be used in the practical part of this thesis will be Philon’s Belopoeica, with the other treatises used to supply supplementary evidence.

Having examined our three main technical treatises in detail, then, the next stage of this thesis is concerned with the practical reconstruction of the catapults themselves, beginning with the methodology used and continuing on to a description and explanation of the building processes used in the reconstructions.

486 Marsden (1999), 169.
Section 2 – Building the catapults

Building Methodology

This section will record and explain the processes followed in the actual reconstructions of the catapults and their ancillary components. The following two chapters will consider the building processes used in the construction of the stone-throwing catapult (*Medusa*) and the bolt-shooting catapult (*Clytaemnestra*). However, before these can be described, the methodologies and techniques which will be used in the construction phase must be explained and justified, and the equipment must be described in terms of its function, how it is used, and how it relates to equivalent tools from the ancient world.

Building materials

Wood

There are several types of wood which could be used for the construction of the catapults. Biton suggests ash as the best wood for the construction;\(^{487}\) Philon is vaguer, giving no particular recommendation for the generic 'old type' engines, and suggesting that his wedge engine should be built 'of elm or ash or whatever someone chooses',\(^{488}\) or even oak.\(^{489}\) Heron suggests that the wood for the stanchions should be tough,\(^{490}\) says that the wood should be sturdy and hard-wearing where wear takes place, and that lighter wood should be used wherever possible.\(^{491}\)

Ash and elm are well known for being both flexible and strong, unlike oak, which (although tough) tends to crack and split, especially when dried out. Elm and oak are considerably more expensive than ash, especially in the quantities required for this project.

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\(^{487}\)Biton, *Construction of War Machines* 44.5-6.

\(^{488}\)\(το\) ὑτο δὲ ἔστω ἤ πτελέῑνον ἤ μελέῑνον ἤ οἷον ἂν τὶς ἐξηται ποιεῖν: Philon, *Belopoeica* 62.6

\(^{489}\)Philon, *Belopoeica* 65.13.

\(^{490}\)δε λαβόντα σανίδα ἐξ εὐτόνου ξύλου ὀρθογώνιον ἀπεργάσασθα: Heron, *Belopoeica* 91.10-11.

\(^{491}\)Heron, *Belopoeica* 102.5-10.
Ash was certainly readily available in the Greek world,\textsuperscript{492} and a timber which Theophrastus recommends for shipbuilding because of its strength and toughness.\textsuperscript{493} Taking the ancient engineers' recommendations into account, it was decided that ash, given its characteristics and that it is recommended by two of the three engineers, would be the most suitable timber to use for the components which needed to withstand hard wear and strong forces (such as the stanchions, hole carriers, case or ladder, sliders, and columns for the catapults' bases). It was decided that pine would be suitable for those components which come under less strain (supports for the base, for instance). Pine, as a soft wood which is commonly available, is a much cheaper though less hard-wearing timber than ash; nevertheless, it is strong enough that it is commonly used in the roof supports of modern houses.

All of the timber which was selected was seasoned, since green wood often warps when it dries out. If green wood were used in building the catapults, there would be a risk that the components might bend out of shape, which could have an impact on their performance over time. There is little doubt that green wood was used when catapults were constructed in the field; engineers would have had to make do with the supplies of wood which were available on site.\textsuperscript{494} However, given the problems involved in working green wood and ensuring that the components, once worked, would not warp out of shape, it is worth speculating that more permanent (especially defensive) catapults would have been constructed using seasoned wood. Meiggs suggests that, given the amount of work needed

\textsuperscript{492}Rackham (2001), 28 and 34, and Meiggs (1998), 42-44. It should be noted that prickly oak was another relatively common tree – Rackham (2001), 8.

\textsuperscript{493}Theophrastus, \textit{Enquiry into Plants} 5.7.3: ἡ δὲ τορνεία τοῖς μὲν πλοίοις γίνεται συκαμίνου μελίας πτελάς πλατάνου· γλισχρότητα γὰρ ἒχειν δεῖ καὶ ἰσχύν ('The crooked-shipbuilding-wood for boats is made of mulberry or manna ash or elm or plane; for it must have stickiness and strength').

\textsuperscript{494}E.g. at Eretria in 198BC, Livy notes that the attacking forces used local timber to construct siege equipment in the field – Livy, 32.16; Livy also tells us that siege engines were constructed from scratch over the course of a few days at Heraclea in 191BC – Livy, 36.22: 'Since there was great rivalry among these men, within a few days towers, rams and every other type of equipment was finished for the attacks on the city' (\textit{horum magno certamine intra paucos dies turres arietesque et alius omnis apparatus oppugnandarum urbium perficitur}). Diodorus also hints that catapults were constructed from scratch at Lilybaeum in 250BC – Diodorus Siculus, 24.1: 'On land they blockaded [the city] from sea to sea with a trench, and they prepared catapults, rams, siege-sheds, and penthouses' (τὴν μὲν γῆν ἀπὸ θαλάσσης εἰς θάλάσσην τάφρῳ ἀπετείχισαν, καταπέλτας δὲ καὶ κριοὺς καὶ χωστρίδας καὶ χελώνας κατασκεύασαν). It should be noted, however, that catapults could be constructed on site from pre-built parts, as hinted by Diodorus Siculus, 20.109.1: 'He began to surround the [enemy] camp with a trench and he sent for catapults and missiles, wishing the besiege it' (...ARGV τὸν περιταφρεύειν τὴν στρατοπεδεῖαν καὶ καταπέλτας καὶ βέλη μετεπέμψατο βοιλόμονος αὐτὴν πολιορκῆσαι).
to construct artillery, 'it may have become increasingly common to take a stock of artillery' with armies into the field.\textsuperscript{495} Certainly, care was taken in the ancient world to preserve all types of wood according to its specific use; Theophrastus comments on the need to keep some timbers dry and others wet.\textsuperscript{496} He noted that the way in which timber was harvested rendered it more or less likely to split, and that different parts of the tree are more or less susceptible to this problem.\textsuperscript{497} He also warned against the use of green timber where holes need to be drilled (which needs to be done frequently in artillery construction) saying that it is harder to work, while for planing and chiselling (which are frequently performed operations while building catapults) he actually recommends green wood.\textsuperscript{498} Four beams, approximately 300cm by 25cm by 10cm were ordered for the construction.

It was decided that the counter-plates (ὑποθέματα) in the stone-throwing catapult should be built from plywood for several reasons: first, ash beams were not available at that time in a suitable thickness; second because the components were experimental,\textsuperscript{499} it was decided that plywood represented a cheaper, yet strong, alternative to pine, to reduce waste if the component proved ineffective; third, plywood is somewhat easier to work, even in large sheets, than a single thickness of wood, and would waste less time if the component failed than if solid wood were used. Plywood was known in the ancient world and was used, for instance, in the construction of curved shields; as with modern plywood, the grain of each layer was set at right angles to the layer above and below it.\textsuperscript{500} There is no direct or indirect evidence to suggest that plywood was or was not used in catapult construction in the ancient world. However, the use of plywood in this capacity should in no way affect the actual performance of the catapult and it was intended that the components, once tested, should be remade in hardwood.

\textsuperscript{495}Meiggs (1998), 172.
\textsuperscript{496}Theophrastus, \textit{Enquiry into Plants} 5.4.2-8.
\textsuperscript{497}Theophrastus, \textit{Enquiry into Plants} 5.5.6.
\textsuperscript{498}Theophrastus, \textit{Enquiry into Plants} 5.6.4.
\textsuperscript{499}See Section 2 'Building Medusa' below.
\textsuperscript{500}Bishop and Coulston (2009), 61.
Metalwork

Wrought iron was also used in ancient catapult construction, mainly to strengthen the wooden components. Philon comments that the weight of the iron used in building a stone-throwing catapult could reach twenty-five times the weight of the calibre for which it was designed.\textsuperscript{501} Nails were also used to fasten the iron plating to the wooden components, but the technical authors do not tell us the kind of metal from which they were made.\textsuperscript{502} Philon notes, however, that in some poorly built catapults the wood was held together entirely by the surrounding ironwork, and recommends that engineers should avoid this by allowing a sufficient thickness for all of the wooden components.\textsuperscript{503} Heron also reminds engineers not to allow nails to penetrate the spring-holes, claiming that they would reduce efficiency.\textsuperscript{504}

During this project, it was decided not to use nails as the main external means of fixing the components together, because they can be very difficult to remove successfully if placed badly. Screws, while anachronistic, can be removed much more easily and repositioned. They are also less likely to cause wood to split (because they follow the line of a pre-drilled pilot hole, unlike nails), and thus have advantages over a more historically-accurate method of fixing the components together. This is important in an experimental piece like this one, because components may need to be changed or altered; components may also need to be taken apart for repair. Therefore, it was decided that despite being less than historically accurate or authentic, it would be acceptable to use screws, as long as their use was noted and justified at each stage. Apart from reducing the risk of the wood splitting, though, and their potential for easy removal, screws have no structural advantage over nails and it was therefore decided by the author that they fell within this project’s aim of creating a functional replica. Nails were, however, used in the construction of the stand

\textsuperscript{501} Philon, Belopoeica 34.17-18.  
\textsuperscript{502} Heron, Belopoeica 92.8  
\textsuperscript{503} Philon, Belopoeica 57.1-27.  
\textsuperscript{504} Heron, Belopoeica 95.3-6.
for the bolt-shooting catapult.\textsuperscript{505}

The washers could be constructed from three possible materials. Heron mentions washers constructed from wood, but these were intended only for the larger catapults,\textsuperscript{506} making them unsuited to this project. The two other materials recommended by the authors are bronze and iron.\textsuperscript{507} The archaeological record has produced a large number of bronze catapult washers,\textsuperscript{508} but as iron is more likely to corrode, it is perhaps not surprising that none has survived.\textsuperscript{509} This does not provide evidence either for or against the use of iron washers in the ancient world. However, since both of the main authors writing about the types of catapults being built for this project recommend both iron and bronze, and since bronze is much more costly and would require specialist bronze casting, whereas iron, or its nearest available equivalent, steel, was both readily accessible and workable, it was decided that for this project it would be most productive to work with steel.

The quantity of wood- and metalwork required in order to build a catapult meant that artillery construction in the ancient world, as in the modern world, was expensive.\textsuperscript{510} Thus, it is clear that in the ancient world, engineers attempted to cut corners or to devise catapults which could be built either more cheaply or by using smaller quantities of expensive materials.\textsuperscript{511} This project also has budget limitations, and it has been necessary at times to substitute cheaper or pre-made materials or components. It should be noted that a great deal of care has been taken to ensure that such steps have only been taken where the functionality of the catapult was not seen to be compromised.

\begin{footnotes}
\textsuperscript{505}See Section 2 'Building Clytaemnestra – Building the stand' below.
\textsuperscript{506}τὸν μαζέων ὁργάνων ὁργάνων: Heron, \textit{Belopoeica} 96.11. What this means in terms of actual size is unclear from the text.
\textsuperscript{507}Bronze: Heron, \textit{Belopoeica} 96.6; Philon, \textit{Belopoeica} 60.2-3. Iron: Heron, \textit{Belopoeica} 83.4-5 and 98.2-3; Philon, \textit{Belopoeica} 60.3-4.
\textsuperscript{508}Rihll (2007), 295-296.
\textsuperscript{509}Rihll (2007), 295.
\textsuperscript{510}Heron, \textit{Belopoeica} 102.9-10, Philon, \textit{Belopoeica} 56.25ff and 62.16ff, and Livy, 34.34.
\textsuperscript{511}Heron, \textit{Belopoeica} 102.5-10: Heron here advises his readers to use lighter, cheaper wood where possible and tells his readers that their catapults should be 'inexpensive' (οὐ πολυδάπανα). See also Philon, \textit{Belopoeica} 56.24, where Philon claims that his own design of catapult will be cheaper to construct than earlier designs (...καὶ ἐπὶ πᾶσι δαπάνην ἐλάσσονα ποιεῖ), and 57.3-16, where he admonishes other engineers for over-enlarging the spring-holes in their catapults to try to get more power out of a smaller machine, to the point where the catapult is practically falling apart.
\end{footnotes}
Washer sizes

Catapult washers in the archaeological record demonstrate a large range of sizes, with the smallest known measuring 34mm\textsuperscript{512} and the largest measuring 160mm.\textsuperscript{513} To keep costs to a minimum, it was decided to use pipes which could be cut to the sizes required, which meant dealing with standardised sizes. However, to maintain as much authenticity as possible, the pipe sizes chosen correspond with washers which exist in the archaeological record and which fit well within the range of sizes which have been found. For the bolt-shooting catapult, it was decided to use a pipe with a diameter of 75mm, corresponding to the Ephyra 5 catapult washer (which, dating from 167BC fits well within this thesis' scope) and only slightly larger than the Cremona washers.\textsuperscript{514} This would, in ancient Greek terms be just over 3 spans (or just under 3.9 dactyls).\textsuperscript{515} This makes the catapult very slightly smaller than the standardised two-cubit (four-span) euthytone catapult as described by Rihll.\textsuperscript{516}

The stone-throwing catapult was given a pipe with a diameter of 100mm. This measurement fits well within the range of catapult washers in the archaeological record, and corresponds with the estimated diameter of the Azaila 3 catapult.\textsuperscript{517} In ancient Greek terms, this would be just under 4.5 spans (or just under 5.2 dactyls).\textsuperscript{518} It is also very close to the standardised 1 mina palintone catapult outlined by Rihll.\textsuperscript{519} Secondly, based on an examination of the possible washer diameters in a spreadsheet before construction commenced, it was very clear that the equipment available would struggle to cope with components any larger than those for a catapult with this diameter of spring-hole. Having

\textsuperscript{512}Ephyra 6, see Rihll (2007), 296.
\textsuperscript{513}Hatra (Iraq) 1, see Rihll (2007), 296.
\textsuperscript{514}Rihll (2007), 295-296.
\textsuperscript{515}Marsden (1969), xix. Ancient measurements could vary significantly from polis to polis, however – see Dike (1987), 26. See also Table 15 below.
\textsuperscript{516}Rihll (2007), 292.
\textsuperscript{517}Rihll (2007), 295.
\textsuperscript{518}Marsden (1969), xix. See also Table 15 below.
\textsuperscript{519}Rihll (2007), 291.
consulted with the timber merchants, it was also clear that obtaining wood of a suitable size for a larger catapult would be costly and delivery would take several weeks. A smaller catapult would also be much easier to transport and move around during the testing phase, and so it was decided to limit the maximum size of the stone-thrower.

**Glue**

There is no indication in any of the artillery treatises that glue was used in the construction of any of the catapults described. Biton's *gastraphetai* would have required the use of glue in the manufacturing of their composite bows,\(^{520}\) but as this is part of the building process which Biton ignores it is perhaps not surprising that he omits this detail.\(^{521}\) Ancient glue was often prepared from animal products, including 'dried fish swim bladders...sinew or hide',\(^{522}\) and comparative evidence also points to the use of animal sinew or fish products as a pre-industrial source of adhesives.\(^{523}\) In the case of glue made from sinew, comparative evidence shows that it can be 'produced from tendons simmered in rainwater...strained off and then evaporated to a viscous solution then cooled and gelled so that it may be stored indefinitely.\(^{524}\) Such glues can take a long time to dry, with high quality composite bows taking at least a year to make,\(^{525}\) though the glue could set faster.\(^{526}\) While these glues would potentially have been of use to those building catapults in the ancient world, theoretically there should be no need to use glue in the actual construction process since it should be possible to use different joints (for example mortice and tenon, dovetail, or rabbet), potentially along with nails, to connect the different components.

\(^{520}\)Miller et al. (1986), 183-184. See also, for example, Coulston (1985), 234 where he describes an undated Roman composite bow with evidence of glue used in its construction, and 243-244, 249-250, and 254-256 where comparative evidence also points to the use of glue in creating compound bows. He also discusses the use of composite bows as part of the *gastraphetes* construction, but unfortunately only in terms of Heron's design – Coulston (1985), 261.

\(^{521}\)Biton, *Construction of War Machines* 45.6-51.4 and 61.2-67.4.

\(^{522}\)Miller et al. (1986), 184.

\(^{523}\)Coulston (1985), 250-251.

\(^{524}\)Coulston (1985), 250.

\(^{525}\)Coulston (1985), 249 and Miller et al. (1986), 184.

\(^{526}\)Coulston (1985), 249.
Modern glues have been used in the building of the catapults, however. This is to compensate in part for some lack of skill on the part of the builders; it has also been used to support otherwise weak joints prior to screws being used to secure the joints. Glue has also been used in an attempt to remedy cracks which have developed in the wood as a result of problems in storage, to reinforce smaller components at risk of breaking, and to attach the bolt-heads to the shafts in order to make them reusable. These uses are completely anachronistic and should be regarded as such.

**Ropes**

The ropes are perhaps the most contentious component of the catapults. The engineers recommend the use of specific types of sinew, horsehair, or women's hair. Epigraphic evidence also points to the use of prepared hair in catapults, though the inscription is fragmentary. The historians also suggest that women's hair was used on occasion. However, these are difficult and expensive materials to procure in the modern world, and require a great deal of processing. Beyond that, specialised skills are needed to spin the fibres, and then the yarn must further be processed by twisting or plaiting it into rope. Despite contacting several rope manufacturers, it was not possible to find anyone willing or able to manufacture horsehair or sinew rope. The next best alternative was to attempt to find a synthetic equivalent to sinew rope, since this is the type of rope emphasised as the best by the engineers.

It is perhaps worth considering at this point what exactly is meant by the term 'rope'

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527 See below, *passim.* There is some evidence for arrowheads being glued to their shafts though – see Coulston (1985), 267.
528 Sinew: Heron, *Belopoeica* 110.4-8 and Vitruvius, *de. arch.* 10.11.9; Hair (generally): Vitruvius, *de. arch.* 10.11.9; Hair (specifically women's): Heron, *Belopoeica* 112.4-6.
529 IG II² 1467, lines 48-56. See also Marsden (1969), 56-57, and Rihll (2007), 70 and 78-79.
530 E.g. at Rome – Vegetius, *Epitoma Rei Militaris* 4.9; Salonae – Caesar, *Civil War* 3.9; and Thasos – Polyaeus 8.67.
531 Heron, *Belopoeica* 110.4-8
as used here.\textsuperscript{532} The words used for 'rope' in the texts are unspecific about its manufacture. Ropes can either be twisted or plaited, but the term used by Heron and Philon, τόνος ('spring-cord'),\textsuperscript{533} refers more to the elasticity of the rope than to how it was made. Vitruvius' term, funis, is also unhelpful, being a generic term for 'rope' or 'cord'.\textsuperscript{534} However, this, along with Heron's description of the method for constructing the bowstring\textsuperscript{535} and springs\textsuperscript{536} for his catapults, demonstrates clearly that some form of rope or cord was used, especially when we consider Heron's use of the verb πλέκειν, which Marsden translates as 'to plait', and can also be translated as 'to twist' when applied to rope.\textsuperscript{537} Clearly, then, we are dealing with sinew or hair which has been processed into some form of rope or cord rather than the springs being made up of individual strands gathered to form a skein.\textsuperscript{538} This does not, though, tell us whether the rope or cord used in the reconstruction should be plaited or twisted. Evidence from decorative scenes in 'non-royal tombs' from Egypt shows that both types of rope were known in the ancient world: examples, much earlier than the time period considered here, show both techniques of rope manufacture, with the majority being twisted rather than plaited.\textsuperscript{539} While plaited rope might have a little more elasticity, for want of better archaeological evidence it was decided to use twisted rope. It seemed likely, too, that the twist already in the rope would both strengthen it and allow it to store more energy.

Philon does, however, describe the thickness of the rope. Assuming that the rope is not pre-stretched, he tells us that it should be \(1/4D - 1/12D (= 1/6D)\).\textsuperscript{540} He then instructs the reader to stretch the cord 'until one third of the thickness is removed'.\textsuperscript{541} The

\begin{itemize}
\item \textsuperscript{532} See also Glossary.
\item \textsuperscript{533} E.g. Heron, Belopoeica 112.4 and Philon, Belopoeica 54.19. See LSJ under τόνος.
\item \textsuperscript{534} E.g. Vitruvius, De Architectura. 11.2. See Lewis and Short under funis.
\item \textsuperscript{535} Heron, Belopoeica 110.9.
\item \textsuperscript{536} Heron, Belopoeica 112.4-6.
\item \textsuperscript{537} Heron, Belopoeica 110.9. See LSJ under πλέκειν.
\item \textsuperscript{538} The skeins are instead made up of ropes looped through the spring-holes and washers.
\item \textsuperscript{539} Teeter (1987), 71. The scenes of rope making (including in the context of ship building, agriculture, and 'other specialized crafts, such as leather-working') date predominantly to the Old Kingdom (c.2686-2181BC) with only two scenes dated to the New Kingdom (c.1550-1077BC) – Teeter (1987), 74-75. Teeter does not give dates for the individual tombs cited.
\item \textsuperscript{540} Philon, Belopoeica 54.22-23 (trans. Marsden).
\item \textsuperscript{541} Philon, Belopoeica 54.23-24 (trans. Marsden).
\end{itemize}
unstretched thicknesses of the ropes for the stone- and bolt-shooting catapults would be 16mm and 12.5mm respectively. Because the rope ordered was pre-stretched, the stretched thickness of the ropes needed to be obtained: with one third of the thickness removed, the sizes of the ropes are 10.6mm and 8.3mm respectively. The exact thicknesses are not available off-the-shelf, and so it was decided to round down the rope thicknesses slightly to 10mm and 8mm which should not affect the performance of the catapults (especially since there could be expected to be some variation in rope thicknesses in the ancient world).

Very little work has been done on the manufacture of sinew rope, with the exception of D. Stephenson's undergraduate thesis, which contained an appendix which apparently described the processes involved in constructing sinew rope. Unfortunately, UCL no longer holds a copy of this thesis, and attempts to contact the author have proved unsuccessful. Schramm was unable to manufacture sinew rope for his reconstructions and instead relied on horsehair, though he does not give an account of the techniques he used to manufacture it. Women's hair is noted in the sources as an alternative material for the spring ropes. Marsden was forced to use 'rubber strands' in his own reconstructions, which again is unhelpful.

Fortunately, interest in this subject has arisen amongst amateur engineers and documentary makers. One test found that two-ply sinew cord behaved 'almost identically' to three-ply nylon in an experiment to test their load-bearing and elastic capabilities. Indeed, towards the end of the tests, the nylon slightly outperformed the sinew which was tested. The sinew cord used was made from deer tendons, an animal from which Heron accepted that sinew could be taken for use in catapults. However, the amateur engineers

542The full title of the thesis was 'Heron's cheiroballistra with an appendix on the manufacture of sinew rope'. It was submitted to UCL in 1995.
543Schramm (1980), 20 n.5 and 29. See also Marsden (1969), 87.
544See note 418 above.
545Johnstone (1957), 95.
548http://ballista.wikia.com/wiki/Case_study:_comparison_of_elasticity_of_sinew_and_nylon_cord. See also Heron, Belopoeica 110.5-8.
conducting these experiments remain anonymous, and there is very little other evidence with which to compare their results. The documentary 'Building the Impossible' conducted tests on rope at Bath University, which no longer holds records of these tests. The documentary itself suggests that '3-strand pre-stretched polyester' rope would be the best substitute for sinew. Nylon does not, from the narration of the documentary, appear to have been tested. Another documentary also tested several types of rope in the same type of weight-bearing and elasticity tests, and again found that nylon was the best material in comparison to sinew. A third documentary used 'sailing rope', though as there are numerous different types of sailing rope made of a number of different materials (including nylon and polyester) the viewer is none the wiser.

In order for any testing at all to go ahead, it was necessary, despite the paucity and generally poor quality of the available evidence, to select a material to use in the spring-ropes. As discussed above, the practical limitations on this thesis (of budget, skills, and time) meant that authentic rope was not an option. In the end, it was decided to choose nylon as a substitute for a number of reasons. First, the agreement between the 'Weapons Masters' documentary and the experiments by the amateur engineers was seen as encouraging. Both of these sets of data show that nylon and sinew have very similar characteristics, and nylon would therefore make a good substitute. Second, polyester performs less well than nylon in tests of breaking strength and elasticity. As Rihll notes, 'the Young's modulus of the material used [for the ropes] must not be too low' in order to have a material which is 'resilient'. The Young's Modulus of sinew is 1.2GPa (gigapascals), while the Young's Modulus of nylon is 2.7GPa. If Rihll is correct,
therefore, we may expect nylon to perform better than sinew, or at least as well, since it has a slightly higher Young's Modulus. Polyester, on the other hand, has a much higher Young's modulus of around 110GPa, meaning that of the available synthetic fibres nylon is the most suitable.

The Ermine Street Guard catapultae

The Ermine Street Guard has two catapults which are relevant to this thesis constructed by Tom Feeley. These are bolt-shooters, one a reconstruction of the Ampurias catapult, and the other a replica of the Xanten catapult. Both catapults are built of ash, with bronze washers. Interestingly, in both constructions carved straight, rather than curved, arms (although these catapults are late enough to warrant the use of curved arms) were used for reasons which the author has been unable to determine. The Ampurias replica belonging to the Ermine Street Guard has the narrow slider and single centre-stanchion of the Vitruvian catapult, which demonstrates that it represents a catapult of a later date than those reconstructed for this thesis. The Ampurias reconstruction is of an almost identical size to the bolt-shooter built in for this thesis; like Clytaemnestra, the reconstruction features steel plating (approximately 2mm thick). The replica of the Xanten catapult also carries plates (of bronze and steel). Both catapults are powered by rope-springs made of nylon, rather than sinew; the bowstring of the Ampurias replica is made of polypropylene rope wrapped in leather, while the author could not determine the

558Kajiwara and Ohta (2009), 85.
559This re-enactment group also has a number of other catapults, including a Vitruvian stone-shooting catapult, a cheiroballistra, and an onager.
560Haines (2007), 134. See also Figs.7-10. See also Wilkins (2000), 91 and Wilkins (2003), 31 Fig. 18.
561Interview with Rob Ingram of the Ermine Street Guard (26/5/14). See also Figs. 11-12.
562Interviews with Tony Segalini and Rob Ingram of the Ermine Street Guard (26/5/14). See also Figs. 7 and 11-12.
563See Figs 7, 9, and 12. Safety was the only issue cited in my interview with Tony Segalini of the Ermine Street Guard (26/5/14).
564See Fig. 9, and Vitruvius, De Architectura 10.10.2-3.
565Interview with Tony Segalini of the Ermine Street Guard (26/5/14). See Fig. 8.
566Interview with Rob Ingram of the Ermine Street Guard (26/5/14). See Fig. 11.
567Interview with Tony Segalini of the Ermine Street Guard (26/5/14). See Fig. 9.
fibre which made up the bowstring of the Xanten replica. Although the Xanten catapult is easily small enough to be hand-held, the Ermine Street Guard has interpreted it as resting on a stand, like the larger three-span catapult. The Ampurias replica uses bolts slightly larger than those used in this thesis at approximately 70cm long, and the Ermine Street Guard interprets them as having three wooden fletches. No missiles for the Xanten replica were available for the author to view. For the purposes of contextualisation, artillery was used by the Romans in a similar way to their Greek predecessors. Artillery was used from high ground to defend trenches, and to remove defenders from their walls. Incendiary missiles were also shot from catapults.

**Equipment**

It was decided early on that it would be impractical to build the two catapults using only hand-tools. The majority of the work on the two catapults has been conducted by either one person (the author of this thesis) or two people working together (either John or Esdi Hughes in collaboration with the author). Since there was such a small amount of manpower available, it would have taken far too long to build the catapults by hand. Moreover, as the power-tools which were used are, effectively, only mechanised versions of the hand-tools which were available to ancient builders (see below), it was considered that the use of power-tools could compensate adequately for the relative lack of manpower.

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568This is probably nylon – interview with Rob Ingram of the Ermine Street Guard (26/5/14). See Fig. 12.
569See Illustration 11.
570Interview with Tony Segalini of the Ermine Street Guard (26/5/14). See also below.
571Interview with Tony Segalini of the Ermine Street Guard (26/5/14). The Ermine Street Guard apparently finds wooden fletches to be more durable than feathered fletches.
572Gilliver (1999), 96 and 110.
573Gilliver (1999), 100.
574Gilliver (1999), 144.
575Gilliver (1999), 147.
576For the other people involved in the reconstruction projects, please see the Acknowledgements.
577Likewise, in the reconstruction of the Olympias, budget limitations and practicality meant that power tools were used – Morrison et al. (2000), 233.
The selection of the power-tools used in this project came from a trial-and-error process which began two years prior to the commencement of this thesis, when the same team was involved in the reconstruction of a Roman-era catapult. During that project, several problems were encountered, and the solutions which we found for them were applied pre-emptively when building the Hellenistic catapults. Most were relatively minor: 10cm-thick beams require longer than standard drill-bits, for example, and large saw blades are needed to cut through it. The wood came from the supplier roughly cut, not planed, which could throw measurements off significantly. Planing with a hand-held power-planer was inaccurate and could leave gouges where the rotating blade cut into the wood, especially at either end of the beam. By the time the Roman catapult had been completed, a planer-thicknesser had been acquired, which allows both sides of a rough-cut beam to be smoothed parallel to each other. Techniques using hand tools, power tools, and measuring equipment had also been improved, meaning that joints could be fitted tightly and accurately. Below is a comprehensive list of the tools used, and how their use relates to ancient carpentry techniques, where there is evidence available. This should be seen as a glossary for all of the equipment mentioned in the following chapters. They are listed in the usual order of use; thus, measuring equipment is listed before cutting equipment, and finishing equipment is listed last (though, naturally, after a rough piece of wood has been cut and planed, it will almost certainly be necessary to make further measurements and cuts). The majority of the discussion of ancient woodworking tools has been taken from Ulrich, who has carried out an extensive investigation into Roman woodworking practices and equipment; a Greek parallel to this work is sadly lacking in modern scholarship.

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578 Alecto was built between 2009 and 2012, using Vitruvius 10.10. Many of the techniques used in building Medusa and Clytemnestra were tested and practised during the construction of Alecto. 579 For details of finds and depictions of woodworking tools from the Roman world, see Ulrich (2007) 337-348.
### Measuring and marking

Table 5:

<table>
<thead>
<tr>
<th>Tool</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compasses</strong></td>
<td>A tool with two straight legs joined at one end with a hinge, used to draw circles. One leg has a spike, while the other has a slot which can hold a pencil or pen. The spiked end is placed at the centre of the intended circle, and the distance between the spike and the tip of the pencil or pen is the same as the radius of the circle which is to be drawn. The tool is then rotated, and a circle is marked.</td>
</tr>
<tr>
<td><strong>Pencil</strong></td>
<td>Used to make temporary or light marks on the wood. The marks can be erased easily if a mistake has been made; they can also show where more permanent lines should be drawn.</td>
</tr>
<tr>
<td><strong>Permanent Marker</strong></td>
<td>Used when it has been decided that a measurement is correct, in order to give a better visual reference when cutting. Fine-tipped permanent markers are used to keep the line as precise as possible.</td>
</tr>
<tr>
<td><strong>Rulers</strong></td>
<td>These are solid metal measures, marked with cm/mm on one edge and inches on the other. They are best used for measuring shorter distances precisely and are especially useful for marking straight lines where the set square is too short or cannot be placed securely.</td>
</tr>
<tr>
<td><strong>Set square/Right angle</strong></td>
<td>A shorter metal ruler set into a plastic straight edge (which also holds a spirit level) at an angle of 90°. This can be held to the edges of cut or planed pieces to wood to determine whether they form a right angle or need further work; it can also be used to draw lines or measure at a 90° angle, e.g. to mark accurately where cuts should be made.</td>
</tr>
<tr>
<td><strong>Tape measure</strong></td>
<td>This is an extending measuring device, with cm/mm and inch divisions marked on the upper surface. A hook at one end can be placed over one edge of the item being measured, while the other end is fixed into a casing into which the entire measure can be retracted. The tape is somewhat flexible, and is best used for measuring relatively long lengths; because of its flexibility, it is less useful for accurate short measurements than firm rulers.</td>
</tr>
</tbody>
</table>

Archaeological evidence shows that measuring equipment was available in the Roman period including bronze rulers with markers as little as 1.85cm apart.\(^{580}\) These

\(^{580}\)Ulrich (2007), 54.
rulers could often be folded, and, according to Ulrich, the usual length of these rulers was one Roman foot (29.6cm); a centrefold in the ruler would quickly give the user a measurement of half a foot. Given that the markings and measurements on the rulers was so much broader than the 2mm margin for error allowed during this project (see below), it is questionable whether ancient carpenters could work to this level of accuracy, or whether they rounded up to the nearest marker. This would have implications for the scaling of the proportional measurements given by Philon and Vitruvius, and the level of consistency found among the artillery engineers. The principles are the same as those found in modern rulers (which, like their ancient counterparts also have a straight edge for marking lines). Whether measuring cords were used by ancient engineers (as an equivalent to modern tape measures) is not clear.

However, one measuring tool available to the ancient engineers but not used on this project was callipers. These tools are like the compasses described above (an equivalent of which was also available to the ancients: an example given by Ulrich is of compasses found in the Giglio shipwreck, which may have been 'of Greek manufacture'), but have curved, rather than straight, legs. They can be used to measure components and to check they are the same size as another given item; Philon recommends their use when checking the thickness of the ropes for catapult springs, since ancient rope would have been less consistent than modern rope in terms of thickness both at the time of manufacture and after being pre-stretched. They could, theoretically, also be used (in conjunction with a measuring device) to work out the fractions and multiplications of length needed to construct the catapult components. There is no direct evidence for this, but it is a plausible technique. Building the components as closely as possible to the specification given by Philon, therefore, is highly desirable even if there is the possibility that the ancient engineers may not have been able to work to that level of accuracy.

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583 Philon, Belopoeica 54.24-25. See also Section 2 'Missiles and Rope'.
Set squares, identical to some of their modern counterparts, have been found in Pompeii, and are shown in relief sculpture.584 Other forms give a number of angles useful to the joiner, ranging from 45° to 135°, in a single instrument.585 This forms the equivalent of a modern protractor (albeit with fixed angles), for the purposes of the engineer.586 A tool for checking that a surface was level was also available in the form of the *libella*. This was an A-shaped adjustable frame, with a plumb line attached; illustrations can be seen on relief sculpture.587 This forms an equivalent to the modern spirit level, although the modern version is more straightforward to use.

It is clear from Heron and Philon's treatises that the engineer constructing a catapult was expected to mark up some of the components before cutting and to create templates for those parts of the catapult which needed absolute exactness.588 Compasses and calliper-gauges may have been capable of 'scribing on a wooden surface',589 and the terms used by Philon and Heron could indicate scratching, rather than drawing.590 Charcoal or chalk could have been used to make temporary marks prior to cutting, but this is without evidence. It does, however, seem illogical to attempt to build a complex and expensive machine without taking care to cut wood to a good approximation of the correct length, since it would be costly to waste good timber and take longer than necessary to build what might have been an urgently needed weapon. Using a pencil in a modern pair of compasses is a very close equivalent, especially since the design and use of compasses has barely changed since the ancient world.

584Ulrich (2007), 56-57, and 56. Fig. 3.48.
585Ulrich (2007), 56 Fig. 3.47.
586A protractor was only needed for the construction of the template for the hole-carrier in the stone-shooting catapult (see below). The majority of the other angles in the reconstructions were 90°, and so only a set square was needed.
588Heron, *Belopoeica* 94.1-96.9 and Philon, *Belopoeica* 52.20-53.7.
589Ulrich (2007), 53.
590E.g, forms of the verb γράφω, which can mean 'I draw', but also has connotations of scratching, grazing, and inscribing: Heron, *Belopoeica* 94.5 and Philon, *Belopoeica* 52.23. See *LSJ* under γράφω.
## Cutting

### Table 6:

<table>
<thead>
<tr>
<th>Tool</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band-saw</td>
<td>An electrically powered saw, with a fine blade fixed vertically. The working height of the blade is adjustable. The fineness of the blade has the advantage that it can be used to carry out detailed work on thin pieces of wood; however, the blade is also very flexible, which means that the blade can bend when being used on thick wood. The blade tends to follow the grain of the wood because of its relative weakness. This saw is also limited as to the width of wood which can be cut using it because of the position of its frame.</td>
</tr>
<tr>
<td>Chisels</td>
<td>Narrow chamfered blades which are sharpened to a point, fixed to handles. Modern blades are normally made from stainless steel, while the handles are normally wood or plastic. Three chisels were used, with the thickness of the blades ranging from 8-14mm.</td>
</tr>
<tr>
<td>Drill (Hand-held)</td>
<td>An electric drill which is hand-held, rather than fixed into position. The drill-bits for this drill are interchangeable and available in a large variety of diameters and lengths. The hand-held drill was mostly used for drilling out the last parts of pilot holes which were started with the pillar-drill, but where the wood was too thick for the pillar-drill to be able to cut all of the way through. The major limitations of this type of drill are that, because it is not in a fixed position, it is easy for the drill to run off-line, making the hole it cuts crooked. By pre-drilling a pilot hole using the pillar-drill, the potential for this is reduced significantly.</td>
</tr>
<tr>
<td>Drill (Mortising)</td>
<td>An unusual drill, since it is used to cut square holes. The drill-bit consists of two parts: a thick drill-bit of the normal type used to cut round holes, and a square-section outer bit, the bottom edge of which consists of four chisel blades. It is limited as to the depth to which it can drill and is problematic to use on particularly thin wood, as the outer part of the drill-bit tapers outward at the bottom. If thin wood is drilled using the mortising-drill, it can become wedged above the lower part of the bit. The drill is fixed into position so that it always cuts holes at a 90° angle.</td>
</tr>
<tr>
<td>Drill (Pillar)</td>
<td>This is a fixed position drill, which performs like the hand-held drill. The drill-bits are fully interchangeable and the same as those used in the hand-held drill. Because of its fixed position, the holes it cuts are always at 90° to the lower edge of the material through which it is drilling. However, it is limited as to the depth to which it can cut.</td>
</tr>
</tbody>
</table>
### Hand saws

Two different types of hand saws were used in this project. The first was a tenon saw, designed specifically for cutting short pieces of wood. This particular saw had the major advantage that the blade was firm, giving a very neat cutting line. It also had offset teeth, which prevented it from sticking and helped in the removal of sawdust. However, it was limited as to the depth it could cut, because a fixture at the top of the blade meant that the top part of the blade was too thick to fit into the line cut by the blade.

The other saw used was a 'universal' saw, which had a finer and more flexible blade. As a result, it could cut much more deeply through the wood, but the flexibility of the blade meant that its cutting line was much rougher.

### Jigsaw

This type of saw was used only to cut out the prototype counter-plates. This is, in effect, an electrically powered version of a bow-saw, and allows thin wood or plywood to be cut roughly. It is hand-held and can be used where wood is too large to be cut using the band saw.

### Table-saws

These are circular saws fixed into position to rotate vertically. Two table-saws were used during this project of different diameters, the larger cutting wood up to 5 inches thick, and the smaller sawing wood up to 3 inches thick. These saws were only used for rough-cutting larger pieces of wood; they left curved marks where the blades had been cutting which were later planed clean. The smaller table-saw could be set at an angle of up to 30° from vertical.

Ulrich notes that finds of ancient equipment often 'closely resemble their modern equivalents', and cites the example of a chisel found in Aquileia which 'looks as if it belongs in a modern wood-worker's toolbox'.\(^{591}\) Drills, too, functioned in a similar way to their modern, electrically powered, equivalents. In the ancient world, drills were operated using thongs or straps which spun the bit in alternating directions (unlike modern drills);\(^{592}\) as Ulrich notes, this means that the spiralling cutting lines which feature in modern drill-bits developed later, since such drill-bits effectively can be driven in only one direction.\(^{593}\) Some examples of drills with spiralled bits do exist, although only the tips appear twisted.\(^{594}\) Modern drill-bits are therefore more efficient (since the spiralling grooves in the

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591 Ulrich (2007), 27.
drill-bits allow the waste wood a route out of the drilled hole), but operate on roughly the same principle as their ancient counterparts. The modern mortising-drill combines these two tools in a way not used by the ancients; however, it places together two technologies which were in existence in the ancient world, rather than developing an entirely new technique.

Several types of saw were used in the ancient world, and were adapted to the tasks for which they were intended. The teeth of the saws were often off-set, according to Pliny, like those of the tenon saw used here; this not only removes sawdust created during the cutting process, but prevents the saw-blade from sticking during its operation. Fine saw-blades were often held in frames, in the same way as in a modern hacksaw (though the original frames were wooden rather than metal); the blades themselves closely resemble those found in the jigsaw and band-saw. Heavier blades were also used: an example found at Verulamium closely resembles the 'universal' saw used in this project, though it is missing its handle. Circular saw blades, like those used in the table-saws, are a modern development. However, thick blades were used by the ancients for larger or heavy cuts, and the principle employed by the circular saws (i.e. round discs with a toothed edge) is effectively an adaptation of a centuries-old technology. Drills, saws, and chisels were available to the ancient craftsmen, and they took forms similar to those used now as power- and hand-tools.

597 Ulrich (2007), 51 Fig. 3.40. For other examples where this may have been the case, see Hodge (1960), 96.
598 Ulrich (2007), 47.
### Finishing

#### Table 7:

<table>
<thead>
<tr>
<th>Tool Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand-files/rasps</td>
<td>Individual tools with either flat or rounded surfaces. On these surfaces are large numbers of smaller, angled blades, which can be used to remove wood or metal either roughly (with larger blades) or more smoothly (with finer blades). These blades are rubbed or pushed by hand over the surface of the wood which is being smoothed.</td>
</tr>
<tr>
<td>Power-file</td>
<td>This is a small version of much larger belt-sanders. A narrow band of sandpaper (1.5cm wide) is slotted onto the device, around two wheels, one of which is powered. Different grades of sandpaper are used for different effects: a coarser grade removes the surface of whatever is being sanded more quickly and roughly; a finer grade gives a neater finish. The power-file is particularly useful when clearing out small spaces which the chisels cannot reach.</td>
</tr>
<tr>
<td>Planer-thicknesser</td>
<td>This is a tool which uses a horizontal rotating blade to remove fine layers of wood from the surface of a plank or beam. When the machine is used as a 'planer' the layer at the bottom of the beam is removed. The wood is passed over the blade with light pressure applied by hand to keep the amount of wood removed even. The amount of wood removed from the surface can be adjusted finely, by less than 1mm if necessary. When used as a 'thicknesser', the wood is passed beneath the blade, on an adjustable table, so that the top layer of wood is removed. This keeps the top and bottom of the beam parallel, allowing the wood to be marked up and cut neatly.</td>
</tr>
<tr>
<td>Router</td>
<td>This is a tool which uses sharp, interchangeable gouges to cut grooves into wood. The gouge rotates, and is pushed downwards and forwards by the operator. A wider channel can be created by running grooves closely in parallel with each other.</td>
</tr>
</tbody>
</table>

Very few planes, which performed the same function as the mechanised version described above, have been found in the archaeological remains, but they were clearly used in the ancient world.\textsuperscript{599} Unlike the modern, powered version, the blades did not rotate, but instead shaved wood off at a fixed depth. It would certainly not be as efficient as the

\textsuperscript{599}Ulrich (2007), 14 and 41-45.
planer-thicknesser. However, the width of wood which the planer-thicknesser can handle is limited by the width of the blade and by parts of the machine which project to either side; the hand-held plane, on the other hand, can be used on any width of wood, simply by planing parallel lines along its length. The type of blades in the ancient and modern equivalents are similar, and fixed at similar angles. Their function is essentially the same, though the planer-thicknesser has the advantage of being electrically powered.

Examples of gouges have been found which fulfilled the same function as those fitted into the router. Unlike the tiny gouges which are fitted to the router (the blades of which measure only a few millimetres), these had long, socketed blades (those found at Silchester range from 26.1cm to 31.5cm) and would have been used in conjunction with mallets or lathes. Although the physical actions needed to operate gouges and the router are fundamentally different, and although the shape of the blades are also dissimilar, the two tools create a remarkably similar effect and are used under similar circumstances (especially when the blade fitted to the router is the simplest, creating a U shape). Rasps and files have also been found, for both metal- and woodworking, and these are very similar to their modern equivalents. The power-file, however, is the least authentic of the tools used in the construction of the catapults. There is no ancient evidence for the use of an abrasive material like sandpaper; perhaps the nearest equivalent would be a grinding wheel, which would be used in metalworking (but not carpentry). Its effect, when used, is similar to that of the type of hand-file with very fine angled blades, but with increased efficiency.

601 Ulrich (2007), 29-30 and 30 Fig. 3.18.
603 Sim and Ridge (2011), 138 and 139 Fig. 74.
## Miscellaneous

### Table 8:

| Clamps | These are used to hold pieces of wood together, or to hold them to the work bench. They can be used to maintain pressure on two pieces of wood whilst glue is setting, to ensure that a piece remains in place while being drilled, or to prevent movement when a piece of wood is being sawn by hand. Clamps come in two forms: C-clamps and sash-clamps. C-clamps have a C shaped frame and grip the wood at either end of the frame's curve. One end is adjustable, and can be raised or lowered by screwing a bar through the frame. They come in a variety of sizes and are the most flexible type of clamp. This type was used most during the building work. Sash-clamps are often used for thicker pieces of wood. The basic frame of the sash-clamp is a bar, with two contact points. One of the contact points is fixed at one end of the bar; the other can be moved along the bar and fixed in set places. The sash-clamp is therefore less flexible, and where the pieces of wood being clamped do not match the fixed positions on the sash-clamp, scrap wood has to be used as packing to make it fit. |
| Mallets | These are hammers (of various sizes) with wooden heads. They are used for several purposes, for example in conjunction with chisels to remove wood from the piece on which work is being carried out. Mallets are also used when piecing the components together, by exerting force on pieces which fit tightly together. |
| Vice | This is a form of clamp which is fixed in place on the workbench, and holds pieces of wood in place while they are being worked. It consists of two plates, one fixed and one moveable, which can be brought tightly together. Its functions closely match those of the clamps described above. It is particularly useful for holding wood at a height at which it can be worked easily. |

There is some evidence for the use of clamps in the ancient world, though none survive in the archaeological record: Ulrich suggests that their frames would have been made from wood, which does not survive well.\(^{604}\) An illustration taken from a painting at

\(^{604}\)Ulrich (2007), 57.
Herculaneum appears to show a C-clamp, but the painting itself is no longer extant and cannot be examined to corroborate the illustrator's impressions. The technology to make the clamps described above was certainly available in the ancient world, but whether this was applied to woodworking technology is impossible to tell from the scarcity of evidence. From a practical standpoint it is possible, though much more difficult, to complete the processes followed in the construction of the catapults without using clamps. Using weights to hold pieces of wood firmly while waiting for glue to set or to keep a block of wood still while it is being chiselled is one alternative; a second alternative would be to have another person hold the piece which is being worked in place. These steps are impractical and can be unsafe, but could be considered feasible.

Wooden mallets are another part of the woodworker's tool kit which do not survive well, but two have survived and are housed in the Comacchio Museum; moreover, illustrations survive in relief sculpture and painting. Round-headed mallets were the usual type used in the Roman world, though the type used in the reconstruction of the Hellenistic catapults were rectangular in profile. Roman mallets were also waisted towards the handle, whereas those used for this project had the same thickness throughout the head. Nevertheless, the tools from the ancient and modern worlds have precisely the same function, and the modern style of mallet can be judged a reasonable substitute for its ancient equivalent.

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605 Ulrich (2007), 57, and 49 Fig. 3.37.
608 Ulrich (2007), 51, and 29 Fig. 3.17.
Summary

Overall, the materials and equipment have been chosen to be as close to those used in the ancient world as possible. Where adaptations and substitutions have been made, every care has been taken to ensure that the performance of the catapults is not affected. Issues of expense and availability of materials have arisen, but either are relatively minor or can be dealt with sympathetically to the overall intentions of this thesis. In particular, the wood follows the suggestions made by the ancient authors, and the metalwork is as close as possible given the availability of materials. The material chosen for the ropes is as close in terms of its functionality to the sinew used in the ancient world as possible, and despite being synthetic should perform as closely as possible to the standards of the ancient catapults. Although mechanised tools have been used to save time, they are adaptations of tools which were in use in the ancient world (the only exception being the power-file). Tolerances may be smaller in the manufacture of these catapults than in the ancient world, but are kept as close to the dimensions given by Philon as can be managed. The building process is, therefore, carefully designed to create functional replicas of catapults used in the Hellenistic period which to a large degree should also work as visual replicas.
Building Medusa

Calculating the dimensions

The first stage in the construction process was to establish which measurements could be determined directly from Philon's *Belopoeica*, and which had to be determined separately based on the available evidence. This was a straightforward process; the dimensions given by Philon, all of which are proportional and based on the spring-hole's diameter, were extracted from the text and entered into a spreadsheet, allowing the actual dimensions for any given catapult to be calculated. As discussed above, it was decided that the stone-thrower, *Medusa*, should be built with a spring-hole of 10cm, making her a 1 *mina* catapult. This measurement was entered into the spreadsheet, and the dimensions were calculated.

Next, the exact shape and size of the hole carrier was established. This was needed because Philon does not provide a proportional set of dimensions for the lengths of the outer-framework beams, telling his reader only that they should be built to a 'suitable' length. Making a template for the shape is somewhat problematic. Philon gives two construction methods. For the first, all of the dimensions required are given, but only one of the angles needed to construct it. In the second method, limited dimensions are given, and only two of the angles (both at 90°). Neither set of instructions is straightforward to follow, even if all the data required were present. On the other hand, Heron's instructions for constructing the shape of the hole carrier are much easier to follow; however, he omits to give any details of the dimensions involved, with the exception that the rectangle drawn at the beginning of the process should have one set of sides twice the length of the other.

609See above.
610See above.
611See Appendix 1, Table 10. Annotated diagrams can be seen in Figs. 87-89. Descriptions of all components may be found in the Glossary.
612ἅρμοζον: Philon, *Belopoeica* 54.5. For full context of this, see Philon, *Belopoeica* 54.4-6. See also Marsden (1999), 161.
613Philon, *Belopoeica* 52.20-29.
614Philon, *Belopoeica* 52.30-53.7.
and that the curved sides of the hole-carrier should be made from 'segments of a circle whose radius is three times the diameter of the spring's hole'.

The problem was solved by applying Philon's measurements to Heron's method. Because the hole-carrier functions in the same way in both catapults and both methods supply similar angles inside the shape, this appears to be a legitimate method for finding the correct shape. Although the rhombuses are almost identical, there is some discrepancy in that in Philon's measurements the width of the hole-carrier is slightly more than half its length. To compensate for this, the lines $A\Delta$ and $\Gamma E$ were extended by this difference before the curved line was drawn. This allowed all of the measurements supplied by Philon to be taken into account during the drafting process, with little alteration to the finished shape as given by Heron. Because Philon fails to give the curvature of the curved sides of the hole-carriers, and actually instructs his readers to use whichever curve they deem appropriate, Heron's suggestion was used. It was therefore determined that the long outer-framework beams should have a minimum length of 85cm, including the relevant dimensions of each component for which measurements are provided by Philon and a 2.5cm overlap at each end to provide support for the tenons of the short outer-framework beams. The short outer-framework beams were determined to have a minimum length of 59cm, including their tenons, based on the overall width of the hole carriers and the long outer-framework beams. These measurements were intended to provide some extra length in case of error.

615Heron, *Belopoeica* 94.1-95.8 (the translation here is Marsden's).
616i.e. the angle segmenting the rhombus for Philon, and the angle of the line $A\Gamma$ for Heron, are dissimilar by 1°, at 28° and 27° respectively
617Philon, *Belopoeica* 53.4-5.
618See above. See also Fig. 25.
619Indeed, error was made in working out the length of the long outer-framework beams. See below.
Building the spring-frame

The first stage in building the spring-frame was to mark out on the wood the dimensions of the components. This had to be done as economically as possible, while at the same time allowing room for error in the initial cuts. Four ash pieces, 90cm by 10cm by 20cm, were cut, each intended to supply one stanchion and one long outer-framework beam. It would later transpire that a measuring and calculation error meant that the pieces intended as long outer-framework beams would have to be used for the short outer-framework beams instead. When this was discovered, the beams were simply cut across their length to give eight short outer-framework beams, each with a length of 45cm. A 120cm long section was cut and planed for the new long outer-framework beams. The beams were then planed smooth to allow the dimensions of the individual pieces to be marked as accurately as possible. The thicknessing facility which is part of the planer-thicknesser was used to keep the two sides parallel. These were then cut out roughly, with a 5cm extension on either side of each marking to allow for the thickness of the saw-blade in the table-saw and to allow a small margin of error and were later planed down to the appropriate sizes.

At the same time, three 95cm-long sections were cut from another large beam. The first two were the basis of the hole-carriers, while the third was intended for all four counter-plates. Again, these pieces were planed smooth so that the template of the hole-carrier could be used to transfer the dimensions onto the wood itself. It would later be established after a process of trial and error that the third section of this timber would not, in fact, have the appropriate dimensions for any, let alone all four, of the counter-plates.620

The hole-carriers' shape was difficult to cut out using either the table-saws or the band-saw. Therefore, a hand-held circular saw was used to cut the shape of the hole-carriers roughly; these were then sanded down to the shape of the template using a hand-
held belt-sander. When this was done, holes were drilled within the spring-hole's circumference, set as closely together as possible to aid with the removal of the wood. The spring-hole was then chiselled from the wood by hand; it took around two hours to remove the bulk of the wood from each spring-hole and a further forty-five minutes to smooth the internal surface using hand-chisels and a power-file. Hand-files and rasps were also used to smooth the internal surface.\textsuperscript{621}

Next, the stanchions and outer-framework beams were cut more accurately to the appropriate sizes. Because they had been cut out roughly and with a (fairly large) margin for error, the pieces were not uniform in size and did not match the dimensions or proportions given by Philon. Each piece, therefore, was planed again on one side, while the opposite side was smoothed using the thicknessing facility to keep the sides parallel. This process was repeated until the correct dimensions were achieved within the 2mm tolerance discussed above. Over-long pieces were cut to the correct length using the smaller table saw.

Tenons were next cut projecting from the stanchions; enough wood, equivalent to the height of the hole-carriers, had been allowed for this when the stanchions were cut out. These were trimmed to 8cm by 3cm. Each stanchion was given a single tenon at each end; Marsden assumed that two tenons would be used at each end of a stanchion, based on Heron's treatise.\textsuperscript{622} Philon himself gives no indication of whether he prefers single or double tenons. It was decided instead, therefore, that in order to ensure the strength of the joint and the accuracy of its fit a single, thick tenon would be used, which could later be adapted into two thinner tenons if necessary.

At the same time, work on the mortices in the hole-carriers was begun with the mortising-drill. Theoretically, the mortising-drill can cut through a thickness up to 220mm, although we were unable to achieve this depth of cut. To compensate, the mortising-drill

\textsuperscript{621}Fig. 25.
\textsuperscript{622}Heron, \textit{Belopoeica} 93.3 and 94.9-10. Marsden (1999), 52.
was used to create large pilot holes, and a hand-held drill was used to make smaller pilot holes at the edges of the mortices. Heron does advise his reader to leave one third of the thickness of the hole-carrier, claiming that this would make the joint stronger and have aesthetic value. Philon is once again silent on this, and in order to make the joints fit accurately we found it necessary to remove the full thickness of the wood. As an aesthetic, rather than functional choice, this would not cause any change in the catapult's performance. The hole-carriers were then upended, and the mortising-drill was used to remove the remaining wood. The internal surfaces were filed using hand tools and a power-file so that the pegs fitted them firmly. The pegs, which had been rough-cut, were also sanded down for better fit. To ensure that each joint could be identified, and the mortices and tenons could be matched up easily, each was marked with a Greek letter (Α, Β, Γ, Δ on the first half-spring and Α', Β', Γ', Δ' on the second), not corresponding to Philon's instructions, but simply for ease of use.

The final wooden component of the spring-frame is the least described in the sources. Heron and Philon's use of the term ὑπόθεμα ('counter-plate') is clearly different, implying that these components had separate roles. In Heron's catapult, the ὑπόθεμα was a support for the washer, and was located beneath it. In Philon's engine, the ὑπόθεμα supported the hole-carrier. Philon's use of this term is more relevant to this study; however, neither of the authors gives any further description of how their components functioned. Therefore, we must use evidence to establish what this component would have looked like and how it would have worked.

Philon does tell us that the counter-plate's height is ¼D, and that the overall height of the half-spring is 9D, exclusive of the height of the lever. Given that there are

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623Heron, Belopoeica 94.10-11.
624Heron, Belopoeica 96.6-98.5, and Philon, Belopoeica 53.8-30. Marsden (1999), 9 and 160, and Schiefsky (2005), 262.
625Heron, Belopoeica 96.6-98.5, and Philon, Belopoeica 53.8-30. Marsden (1999), 9 and 160, and Schiefsky (2005), 259 and 262.
626Here and below, the letter D represents the measurement of the diameter.
627Philon, Belopoeica 53.16-18.
two washers (one at the top of the half-spring and one below the half-spring) with a height of \(\frac{3}{4}D\) each (i.e. 1.5D in total), two hole-carriers, each with a height of 1D (i.e. 2D in total), and one stanchion with a height of \(5\frac{1}{2}D\), then a total of 9D in height is established without the height of the two counter-plates of each half-spring being taken into account. This means that not only must the counter-plate sit underneath each hole-carrier, but that each must sit within the half-spring and between the side- and counter-stanchions. They must be of a size which is capable of supporting the hole-carrier, and they must also connect to the stanchions, and possibly the outer-framework beams, in order to remain in position and support the hole-carriers.

Marsden seems to argue that the outer-framework beams are held in place simply by being fitted tightly around the rest of the spring-frame (i.e. both half-springs); this seems both implausible and impractical. Wood, as an organic material, changes its shape under different weather conditions; in damp conditions, for example, it tends to swell. These changes are not uniform across the components, which would mean that a tight framework might fit well at one time, but not at another. Moreover, even a tight fit could work loose, particularly if strikes from the catapult's arms caused vibrations in the half-springs. A design for the counter-plate, therefore, which could be used to connect the outer-framework beams to the rest of the half-spring would not only enable the component to work alongside Philon's specifications, but would help to solve the problem of how the outer-framework is connected to the rest of the spring-frame. The design for the counter-plate, and how it fits into the rest of the spring-frame is illustrated below.  

This is an entirely new solution to both of these problems. Schramm appears, in his diagrams of the palintone engine, to show a similar method by which the hole-carriers could connect to the outer-framework; however, the diagrams are unclear and inconsistent, and could simply show the hole-carriers resting on top of the framework. In none of his

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628 Philon, Belopoeica 53.7-15
629 Marsden (1969), 32.
630 Figs. 26 and 28-30.
diagrams is the counter-plate illustrated separately, nor does he discuss it in the section of his work on his own reconstructed stone-shooting catapult.\textsuperscript{632} Marsden does not engage at all with the problematic nature of this component, noting only that Heron and Philon's uses of the word ὑποθέματα are distinct from one another.\textsuperscript{633} While there is certainly not enough evidence from the technical treatises to guarantee that this solution is the one used by ancient engineers, I would argue that its simplicity and effectiveness make this particular interpretation both appealing and persuasive.

Having cut out prototype counter-plates, it was necessary to fit them into slots on either side of each stanchion's tenons. There was some unevenness on the counter-plates' tenons, which was sanded off using the power-file. The positions of the slots were marked on each stanchion by placing the counter-plates' tenons on either side of the stanchions' tenons and tracing their edges. These were then squared off using a set-square to allow some room for adjustment. The outer edges of each slot were then cut using the band-saw, and between these two cuts the wood was sawn into thin slivers.\textsuperscript{634} This made it easy to chisel the remaining wood out using hand tools. The slots were then sanded smooth.

It was now possible to connect the short outer-framework beams to the half-springs. Each beam was marked with a central portion, which represented its length according to Philon's dimensions (i.e., the same as the overall length of the hole-carrier, 32cm). An additional 6cm at each would form the tenons to connect to the long outer-framework beams. The half-springs were assembled with the counter-plates in position. One end of each short beam was lined up with the edge of a stanchion, while resting on the tenons of a counter plate, allowing the tenons' positions to be marked onto the short beam. This was done for each counter-plate and each short beam. They were marked with the letters, as above, so that they could be matched up on assembly. The markings were squared off using a set-square, to allow for some slight variation in the straightness of the counter-plates'

\textsuperscript{632} Schramm (1980), 54-57 and Tafel 4.
\textsuperscript{633} Marsden (1999), 53, 54, 160, and 164.
\textsuperscript{634} Fig. 27.
tenons and to allow the mortices to be drilled at 90°. The mortices measured approximately 2cm by 2.5cm, the same size as the tenons. Unfortunately, the mortising-drill bit was of an unsuitable size, and so it was decided that it would be more practical to make pilot holes using a pillar drill and use a larger drill-bit (in a hand-held drill) to remove the majority of the remaining wood. The remaining wood was chiselled and filed out by hand and with the power-file. After the mortices were completed, the beams' ends were marked for tenons (2.5cm²) to be cut using the band-saw.

The long outer-framework beams were next fitted to the shorter ones. The same method as that used for the short beams was used to mark the mortices' positions, this time using the shorter beams as a frame of reference. The centre point of each of the long beams was found and marked. A distance of 7.5cm from that point was measured and marked to either side (a length of 15cm in total, representing the width of the table board and ladder). These marks were lined up with the inner ends of the counter-stanchions, and the positions of the tenons on the short beams at each sides of the half-springs were marked and then squared off. The mortices were drilled and finished in the same way as above. Next, the spring-frame was assembled to ensure that the fit was both accurate and solid.

Having assembled the spring-frame, it was possible to tell where the spring-holes would be positioned on the counter-plates. These were then drawn onto the counter-plates, using the spring-holes in the hole-carriers as templates. The spring-frame was then dismantled, and the spring-holes were cut out of the counter-plates in the same way as in the hole-carriers. At the same time, the hole-carriers' edges were trimmed using the band-saw to allow the long outer-framework beams to fit snugly against the stanchions. This was necessary because there were some slight gaps between them as a result of minor inaccuracies made when the hole-carries were originally constructed.
**Building the table, ladder, slider, and winch**

The table is formed from three pieces: the top and two side pieces. All three pieces were cut, planed, and trimmed to size. These were then glued into place and held with clamps until the glue set. Screws were used to hold the pieces together for the reasons outlined above. As this component is a support, rather than a functional part of the catapult, this is highly unlikely to affect the catapult's performance.

The ladder was the next component to be constructed. Like the counter-plates and outer-framework for the spring-frame, there is very little detail to explain the ladder's construction. We can establish that there must be at least six rungs, because they must be placed at intervals of 4D (i.e. every 40cm). This length of the ladder (190cm) does not divide equally by this measurement, and so it was decided to place an extra rung at the back of the ladder for support (i.e. to keep the side-poles of the ladder an appropriate distance apart at the end where the winch is situated). The rungs were quite short and thin (12cm by 1.67cm by 3.33cm), which has a downside: because they are so small, it was too difficult to secure them using the same mortise and tenon method used in the components above. It was decided instead to use a similar method, increasing the rungs' length from 12cm to 17cm and using the extra wood for tenons. These would be inserted through mortices in the side-poles, and dowelling pegs would be placed through mortices drilled in the tenons to hold the rungs in position.

The side-poles of the ladder were rough-cut and then planed before being trimmed to size. The poles were then marked with the approximate position of the rungs; however, their vertical positioning is not described by Philon, and deduction must be used. The missile must be propelled from the centre of the spring-frame (and so must be shot from its vertical midpoint), because this allows equal power to be stored in the halves of the spring.

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635 As discussed above, this glue was used only to speed up the building process. Glue was probably not used by ancient engineers building this type of catapult.


637 See Fig. 33.
above and below the arms. This means that the slider must be raised to 27.5cm from the bottom of the stanchions. The height of the table covers 17cm of this, and the thickness of the slider takes up another 2.5cm. The height of the ladder provides at least another 10cm, meaning that the rungs should be placed towards the top of the ladder. To ensure that the slider cannot move off or away from the ladder (and thus risk the potential for the missile to shoot off course), the height of the side-poles must be extended by at least 3-5cm. A groove must also be cut straight along the slider to direct the missile.

Having established these parameters, it was possible to mark the positions of the rungs onto the side-poles. Initially, these marks were drilled out using the pillar-drill to provide a pilot hole for the mortising-drill. However, after the first square hole was made using the mortising-drill, it became evident that this was a tool which was inappropriate for the task, because of the problems of using the mortising-drill with thin wood as outlined above. Therefore, it was decided that it would be better to drill out the corners using the pillar-drill and to chisel out the rest by hand. The holes were sanded using the power-file, because chiselling gave the holes a rough finish. Sanding the mortices also made it easier to fit the pegs from the rungs more precisely.

The rungs were then fitted to the ladder, again using a system in which each mortice and tenon was marked with a Greek letter so that they could be matched up easily on re-assembly. Again, these letters do not correspond to any set out by the technical authors and were only for ease of construction. It was discovered at this point that the tenons were not long enough to allow a dowelling peg to be fitted through them; indeed they actually fitted flush with the outside edge of the ladder. However, since the fit was quite tight, it was decided that this was not problematic. Problems did arise, however, when removing some of the rungs from the ladder, especially where they were fitted particularly tightly, because the rungs were so thin that parts of the tenon snapped off. It was

638 Philon, Belopoëtica 54.6-7 and 54.10.
639 Fig. 31.
anticipated that if the catapult were put together and dismantled frequently, the rungs would have to be replaced over time.

It was later discovered that part of the weakness in the tenons of the rungs was caused by the grain running at 90° to the tenons, rather than from one tenon to the other. This meant that when the tenons were hammered into the mortices the wood frequently split along the grain. These rungs had to be replaced, and to avoid such problems in the future the replacement rungs were cut with the grain running in the opposite direction. It was also decided (from the viewpoint of safety, rather than from any historical evidence) to fix the rungs into the side-poles permanently, to reduce the risk of the rungs' tenons being damaged under transport and failing while the catapult was in use. Therefore, the tenons (which were already tightly fitted into the mortices of the side-poles) were glued into position.\footnote{Fig. 32. Again, this use of glue is most likely anachronistic.}

The slider was much simpler to construct, since it consists of a single plank with a wide groove running down the centre to direct the missile with the trigger mechanism attached to the back. We are not given detailed dimensions for the slider; Philon only tells us that it should be an appropriate size for the ladder.\footnote{Philon, \textit{Belopoeica} 54.14-15: καὶ χελωνίου μῆκος μὲν ποιεῖν σύμμετρον, πλάτος δὲ ἁρμοστὸν τῇ κλιμακίᾳ.} Vitruvius gives us a suggested length of $11.5D$ (115cm, in this case),\footnote{Vitruvius, \textit{De Architectura} 10.11.7.} but it was decided that it would be practical to make the slider for the Greek catapult slightly shorter than this, at 90cm. This meant that the slider would always be in contact with at least two of the rungs (and would therefore be kept stable), but at the same time would be economical in its use of wood, a concern which Philon expresses elsewhere in his work.\footnote{Philon, \textit{Belopoeica} 62.16-17.} This should be regarded as the shortest practical length for a slider in this type of catapult: any shorter, and the slider would be unstable on the ladder.

A groove, to guide and support the missile, was cut into the slider using a router. A
split had developed at one end of the slider which needed to be avoided during the routing so that it was not made worse. Philon gives no guidance as to how deep the groove should be, and neither does Heron or Vitruvius. A depth of 5mm and a width of 5.5cm were estimated to be appropriate; this allows half of the thickness of the slider to support the missile and enough space for the type and diameter of missile to vary, while also giving sufficient width on either side to guide the missile. The bit used in the router created a U shape, giving a smooth finish.\textsuperscript{644}

The trigger mechanism, which was placed on the back, performs several functions at once and is made up of a number of smaller pieces. Philon gives us nothing to go on for the design of the trigger, and Vitruvius gives us only some of the details required, though Heron does give us some information.\textsuperscript{645} Not only does the trigger mechanism carry the trigger itself, but (in accordance with Marsden's interpretation of Heron and Biton's ratchet system which runs down the side of the ladder)\textsuperscript{646} it also holds the pawl, allowing it to move while keeping it in the correct position in relation to the ratchet teeth. The component, then, consists of a four-sided metal box, with two uprights at the front to hold the trigger bar; this was shaped like a single bent finger (or claw), rather than the two-pronged version used in the bolt-shooting catapult, so that it would more easily release the loop on the back of the sling.\textsuperscript{647} Set at the back and to the right of the trigger bar (as viewed from the front), an upright round bar is fixed into position, to hold the trigger release, which in turn sits under the trigger bar and can be rotated to allow the trigger to lift and release the missile. A third upright is fixed to the left of the other two uprights, supporting a bar to hold the ratchet pawl. A curved bar was welded to the back of the box, projecting 2cm from the centre, onto which the winch rope could be tied.\textsuperscript{648} Holes were drilled into

\textsuperscript{644}See Fig. 45.
\textsuperscript{645}Vitruvius' details concern his bolt-shooting catapult, and therefore must be adapted for the stone-shooter: Vitruvius, \textit{De Architectura} 10.10.4 See also Heron, \textit{Belopoeica} 111.1-8.
\textsuperscript{646}Marsden (1999), Plate 4. See also Biton, \textit{Construction of War Machines} 45.8-47.1, 50.1-51.4, and 63.9-64.3 and Heron, \textit{Belopoeica} 79.6-81.2.
\textsuperscript{647}Heron, \textit{Belopoeica} 111.1-8.
\textsuperscript{648}Fig. 36.
the box to allow it to be fixed to the slider.

It should be noted that the majority of the measurements used in this component are speculative and have been decided pragmatically, based upon both what worked as the component was constructed and previous experience in building a Roman bolt-shooting catapult. Because of an error in the construction (the welder who was given the job of putting the box together misread instructions that the dimensions given to him were internal rather than external figures), the box is narrower than was intended; however, given the component's speculative design and that under test it was found to work well, this was not considered enough of a problem to warrant rebuilding it. As a result, the slider needed to be made narrower at one end so that the box could be fitted. Nevertheless, because of the problems which had arisen in the construction of the box, it was screwed onto the slider, rather than permanently fixed, so that if problems were to arise it could be removed and adjusted.

The winch was relatively simple to construct. A block of wood measuring approximately 30cm by 30cm by 10cm was cut and planed, from which two winch drums with a diameter of 25cm and a thickness of 5cm could be cut. Unfortunately, because of the thickness of the block, neither the table-saws nor the band-saw could be used. This meant that block had to be cut by hand. The block was marked up with a cutting line using a permanent marker so that it would show clearly. The corners at the top of the block were then cut diagonally using the tenon saw until the cuts met, and then the remainder was cut using the 'universal' saw. Several hours of hand-sawing were needed to separate the pieces, which were then planed.

The centre of each block was found by drawing diagonal lines from corner to corner. Using the centre point, the outline of the winch was drawn using a compass and pencil, which was then marked over with a permanent marker for clarity. The edges were

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649 This measurement was adapted from Vitruvius' recommendation for the size of the winch drum for his bolt-shooting catapult, which he suggested should be 2.5D: Vitruvius, *De Architectura* 10.10.5.

650 Fig. 34.
trimmed using the band-saw. This was tricky because, as noted above, the blade had a
tendency to follow the grain of the ash wherever it could. A series of small, straight cuts
had to be made, and, as a result, the edges of the winch drums appear a little rough. The
cutting had to be finished using the hand-saws, which gave an even rougher finish because
of a failure of the band-saw.651

It was decided to use wooden axles for the winches, because these could be fitted
more quickly and easily than metal ones. At the time, some of the metal working
equipment and the people trained in its use were unavailable. Vitruvius does not tell us
whether to use wooden or metal axles,652 and Philon and Heron do not mention them at all.
A metal axle might be considered safer, since it would have a much higher breaking strain
and that, should it break, there would be no risk of flying splinters. However, on a practical
note, wooden axles can either be glued or hammered into place, depending on the tightness
of the fit. A wooden axle which is thicker than a metal axle might be should be able to take
the strain placed on it by the catapult. A wooden axle is also much cheaper to manufacture
than a metal one, and this would surely have been the case in the ancient world too,
especially if a catapult were being assembled in the field. Should the axle fail, the strain
would be taken by the ratchet system, thus allowing safety concerns to be met. It would
also be possible to change the axle for a metal one later. A piece of hardwood dowelling
16mm in diameter was chosen, as this was considered sturdy enough; a 16mm hole was
drilled through the centre of each winch drum, and, as a test, the dowelling was hammered
into place. The dowelling fit so tightly that it had to be hammered out, since it could not be
removed by hand. Four smaller holes were drilled into the sides of the winch drums at 90º
to each other, so that the winch could be turned using a handle.653 To hold and support the
winch larger, 18mm holes were drilled at the back of the ladder, one through each of the
side-poles, giving enough room for the axle to rotate, but not allowing the axle to be over-

651Figs. 34-35.
652Vitruvius, De Architectura 10.11.8.
653Fig. 35.
Small plates were later screwed onto the winch drum and axle to keep them fixed together.

The ridge-poles (πτερύγιον) are, again, components of the catapult not described in detail by Philon, though he does give us their dimensions (19D by 0.25D, therefore an actual size of 190cm by 2.5cm by 0.5cm); the only other detail he gives is that the slider runs through them. Their placement, then, could be in any one of several different ways. Marsden interpreted them as parts of a dovetail, as in the bolt-shooting catapults, to help keep the slider running in its proper course. However, this interpretation does not fit exactly with the dimensions described for either the slider or the ridge-poles, since the width of the ridge-poles would be too narrow to hold the slider if cut at an angle. The term πτερύγιον could fit with Marsden's interpretation, given its various translations, including 'anything like a wing', 'fins of fish', 'horns of the horned owl', and 'pointed roof or peak', however, where Vitruvius uses this term, it appears to be distinct from the dovetail in which he describes the slider resting. Several different ways of fitting the ridge-poles were explored, before being abandoned. First, they were set up as struts running up to the spring-frame from the ladder, as in Vitruvius' design, but they were too long and slender to give support to the catapult's frame. Next, they were laid along the ladder, attached to the top of the side-poles. In practice, though, they prevented the slider and trigger from moving properly. Thirdly, a compromise between Marsden's interpretation and the second attempt was tried, with the ridge-poles shortened, so that they would not get in the way of

654 Figs. 31-33 and 36.
655 Philon, *Belopoeica* 54.12-14: ποιεῖν δὲ καὶ τὰ πτερύγια, δι’ ὧν τὸ χελώνιοι ἄγεται, μῆκος μὲν ἔχοντα τὸ ἴσον τῇ κλιμακίδι, πλάτος δὲ διαμέτρου τέταρτον μέρος, πάχος δὲ ὀκτωκαιδέκατον μέρος τῆς διαμέτρου. Marsden (1999), 162, Figure 4. See also Heron, *Belopoeica* 85.8-10 for a description of the dovetail in the bolt-shooting catapult.
656 Marsden (1999), 162, Figure 4. See also Heron, *Belopoeica* 85.8-10 for a description of the dovetail in the bolt-shooting catapult.
657 LSJ – πτερύγιον. It should be noted, however, that the LSJ when referring specifically to the passage, translates the term as 'flanges holding the projection of a torsion-engine'
658 Vitruvius, *De Architectura* 10.11.7-8: ex his dentur duae partes et membro quod Graeci χελώνιον vocant, latitudine foraminis II, crassitudo 9, longitudine foraminum XI et semis. extantia chelonii foraminis S; pterygomatos foraminis 9. quod autem est ad axona, quod appellatur froms transversarius foraminum trium. Interiorum regularum latitudine foraminis E, crassitudo 1; chelonii repleum, quod est operimentum, securicula includitur in scapos climacidos... (the addition of bold lettering to the text is my own).
659 Vitruvius, *De Architectura* 10.11.9.
the trigger mechanism, but would still keep the slider in place. This was not a happy solution, and problems arose later (see below). More work will be needed in the future to establish exactly how this component fitted into the catapult.

The ratchet system is relatively simple, and follows the pattern set out by Marsden in his reconstruction of a Roman bolt-shooter and the ancient engineers' descriptions. A pawl projects from the trigger mechanism, and engages with teeth which run along the side of the ladder. It was decided that the pawl itself should be of the simplest design possible, and so a design of a straight bar with a length of 19cm, a width of 4cm, and a thickness of 8mm was chosen. The bar had one end cut off at an angle of 45° to allow it to engage with the teeth. A hole of 6mm was drilled in the centre of the squared end, so that it could be fitted onto the trigger mechanism.

To save time and to follow the system which clearly worked well for Marsden, the angle at which the teeth sat on his design was measured, based on an illustration in his two books. Using this, it was possible to establish that his ratchet system had teeth set at an angle of approximately 10°. The teeth were sawn from an off-cut of ash with a thickness of 2.6cm and a height of 4.5cm. This allowed the teeth to have a height of 2.5cm and a length of 11cm, supported by a band underneath 2cm high. They were sanded, because hand-sawing was not completely accurate, and the beams carrying the teeth were glued firmly into place. It was decided not to screw the beams onto the ladder immediately, because there had been some problems with the ash splitting; this was reserved as an option which could be used if any problems appeared in the testing phase.

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660 Just visible in Fig. 45.
661 Marsden (1999), Plate 4. See also Biton, *Construction of War Machines* 45.8-47.1, 50.1-51.4, and 63.9-64.3, and Heron, *Belopoeica* 79.6-81.2.
663 The equivalent component for the bolt-shooter is illustrated in Fig. 34. The stone-shooter's ratchet system can be seen in Fig. 47.
664 See Section 2 'Building Clytaemnestra' below.
Powering the catapult: the washers, arms, and bowstring

The washers were made from steel pipe, with an internal diameter of 10cm and an external diameter of 11.5cm (a thickness of 0.75cm). Flanges with an internal diameter of the same as the external diameter of the pipe and a thickness of 1cm and width of 2cm were welded 1cm from the bottom of the pipe, to sit above the bottom washer. The bottom washers were rectangular, with measurements of 15.5cm by 16.5cm, with a circular hole in the centre to hold the top washers. The flanges of the top washers had sixteen holes each drilled into them, which is more than is represented in the archaeological finds; however, in the interest of being able to fine tune the torsion during the testing process, it was decided that this would be an acceptable variation. It was later found that these holes were not needed after the initial torsioning and that the force of the twisted ropes held the washers in place. A hole was drilled through each corner of the bottom washers, so that they could be screwed into position. Finally, recesses were ground into the tops of the top washers to allow 'levers' (ἐπιζυγίς), measuring 30cm by 3.5 cm by 2cm, to be welded into place. The levers are gripped by a torsioning tool, allowing them, and the ropes they hold, to be twisted.

The arms were the simplest components to make. Stone-shooting catapults appear to have had straight arms continually from the time torsion artillery was developed. Philon gives exact measurements for the arms (a length of 6D and a thickness of 0.5D) giving actual measurements of 60cm and 5cm respectively. To allow a margin of error, each arm was cut slightly thicker than it should have been all around; the excess was then planed off. Later, when the catapult was assembled, notches were sawn into the arms to keep the bowstring in position; the depth of each of the cuts was slightly thicker than the

665 See above and Fig. 37.
666 Fig. 38.
668 See 'Introduction' above.
669 Philon, Belopoeica 53.24-25 and 53.29-30.
670 See below.
The bowstring's construction was that of a modern bowstring, though it was made thicker and longer than those of modern sports bows. Philon gives us the length of the bowstring (νευρά) as 2.1 times the length of the arm (i.e. 12.6D or 126cm in this instance). Marsden interprets this as referring to the entire sling, which seems somewhat excessive. A more nuanced reading would interpret this as the bowstring including the sling. It was decided to use dacron (a type of nylon) for the bowstring, which is the standard material used in modern bowstrings. There were two main reasons for this choice: first, dacron is less affected by changes in humidity than natural fibres such as linen or sinew; thus, it can be stored more easily and used in a variety of weather conditions. Second, it is more readily available in appropriate thickness and strengths, and is cheaper to buy. As in the case of the use of nylon for the spring-ropes (discussed in more detail above) amateur experiments seem to show little difference in the elasticity and weight-bearing potentials between sinew and nylon as materials, and nylon outperformed the sinew during the first round of tests. However, this evidence is problematic because no authors are listed and we have no further evidence to confirm or contradict these results. A distinct lack of research in this area makes it impossible to tell exactly the extent of the difference in performance between these two materials. It has been suggested in the academic literature that polyester makes a poor substitute for sinew, but nylon performs significantly better than polyester both in terms of its breaking strength and its elasticity.

Reconstructed hand-bows may have some bearing on this discussion.

Unfortunately, the materials used for the bowstring are often omitted from publications. Miller et al., for example, note the importance of sinew and horn for their reconstructed...
bows, but fail to mention the material used for the bowstring. Prior's reconstruction of the Meare Heath bow likewise neglects to mention the material used in making the bowstring. In addition, Bergman et al., who discuss a number of replica bows, also leave out the details of the materials used in the bowstring in their otherwise comprehensive descriptions of the bows themselves. However, what can be said is that the bows which used sinew elsewhere in their constructions greatly improved their performance compared to the bows which did not use sinew, in terms of the distance to which a missile could be shot. Those with a sinew backing also showed an improved velocity of shot as compared to those bows where a sinew backing was not used (for example, the Bergman et al. note that a composite bow with a 60lb or 27kg draw weight can shoot a missile at the same speed as a longbow with an 80lb or 36kg draw weight). In part, though, some of this better performance could be attributed to the shape of the bows, since their design with its shorter limbs 'allows for a much more efficient transfer of energy' when combined with the sinew component.

A bowstring jig was used to construct the bowstring. First, the jig was set to the correct length for the bowstring. The material for the string was wrapped fifteen times around the four uprights at both ends of the jig, which were set at 90° to the central adjustable bar. One of the short ends of the rectangle which was formed by this process was then 'served' to the length required to slip around the arms of the catapult (25cm). The uprights on that end of the jig were rotated through 90°, to run in the same direction as the central bar, and the ends of the 'served' part were joined with 2.5cm more of the serving.

Miller et al. (1986), 183.
Bergman et al. (1988), 662-666.
Bergman et al. (1988), 666.
Bergman et al. (1988), 666 and 667 Fig. 5.
Bergman et al. (1988), 666.
Fig. 39.
This is a technical term for whipping the bowstring (i.e. wrapping thicker cord tightly around the outside of the core dacron to strengthen it). A piece of equipment known as a 'serving tool' is used which helps to keep the serving thread at the correct tension; it also helps to guide the thread and keep the layers of cord close together on the bowstring. See Fig. 16.
along the length of the doubled bowstring. The same was done at the other end of the jig. The centre of the bowstring was served and, to give the trigger bar something to grip, was turned into a loop 2.5cm by 2.5cm. In practice, though, it emerged that the bowstring was pulled very tightly to the extent that the loop became too small to be of any use. Therefore, the serving which held the loop in place was cut and the trigger bar was left to pull a plain serving band, as is used on normal bowstrings. The bowstring was then twisted to the exact length required, and the jig adjusted to hold it. The string was left overnight under tension.

The sling itself was constructed using leather, rather than cloth, partly because of leather's toughness, and partly to save some time on sewing (if cloth had been used, the edges would have had to have been hemmed, extra reinforcements would have been needed where the sling attached to the bowstring, and care would have had to have been taken to ensure that the cloth was cut at a suitable angle in relation to the warp to avoid too much stiffness or stretch). Philon gives us no dimensions for the sling itself, but they can be estimated using the other components. The sling must be at least as wide as the slider, i.e. 7.5cm, and it must be high enough to grip the missile, and so a height of 5cm was chosen; a rectangle of these dimensions was cut from a thick but flexible leather hide, with strips of the same height and approximately 1cm width also cut out. Slits were cut horizontally in the rectangle, with a gap of approximately 1cm left at each side. The strips were then woven through the long slits to give the sling extra strength and to reduce the chance of the leather stretching. They were sewn into place at top and bottom using thick thread. Further slits were made vertically in the spaces at the sides of the sling to allow it to be threaded onto the bowstring. 685

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685Fig. 41.
Assembly

The catapult needed several people for its assembly. The first components put together were the half-springs, followed by the spring-frame itself. There was some difficulty in assembling the spring-frame; because of the how the wood was affected by changing atmospheric conditions whilst in storage, the long outer-framework beams must be put in place in a particular order, otherwise the whole thing will not fit together. Instead, the half-springs begin to rotate towards the centre, meaning that the long outer-framework beams cannot slot on the shorter ones. Once the correct order in which to set up the spring-frame was established, a technique for hammering the pieces together was developed. It was found that the best technique involved having one operator on each side of the upright spring-frame. The upper long outer-framework beams were put in place first; these were hammered into place by the person on the same side, using wooden mallets (which are less damaging to the wooden components than hammers). Working from the outside inwards, and with both people hammering at the same time, was more successful than trying to hammer one long outer-framework beam and then another. When one was hammered on first, the vibrations from the placement of the second one made the first move, and required further hammering to keep it in position.

The next stage was to fit the rope-springs into the spring-frame, through the spring-holes. Approximately 45m of rope was used in each rope-spring. One end of the rope was tied to the lever at the top of the spring frame using a reef knot, and the loose end was passed through the washer and down through the washers at the bottom of the spring-frame. To make the process very straightforward, the spring-frame was laid on the ground
on its front. This process follows that outlined by Heron. The arms were inserted before the rest of the catapult was fixed together. It was much easier to put them in place while the spring-frame was still on the ground and to ensure that they were level. It could also be ensured that they were not pushed too far through the rope-springs. Torsioning was also done at this point; the position of the spring-frame allowed the operator to assert more power on the washers (and, therefore, the springs) than if torsioning were attempted with the spring-frame attached to the other components. This was done using a torsioning bar. The long bar provides leverage for the operator, allowing the ropes to be twisted relatively easily. This tool is mentioned only by Heron and is a very simple device. Practicality suggests that a tool similar to this is likely to have been used, and given that Philon wrote about the principle of leverage we must be open to the possibility that he would have used something similar on his own engines.

As has been noted above, the ladder was already permanently assembled. However, it was still necessary to attach it and the table to the spring-frame. There is no guidance in the technical manuals to show how these could be achieved, and so ingenuity was required. Given the types of components, the most simple, effective, and practical solution seemed to be to lash them together. This would allow them to be assembled and dismantled quickly and easily. This method also allowed for variations in humidity, and thus for any swelling of the wooden components. It would also allow a small amount of movement within the

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686 When this was attempted in the earlier project to reconstruct a Roman bolt-shooter, the catapult was otherwise fully assembled during the rope fitting. This made it difficult to equalise tension in the springs, since the washers at the bottom of the spring-frame were looser than they should have been because they had to be held in place by hand. Moreover, the catapult was unstable on its stand, making the work more difficult and dangerous. Therefore, here the best approach was to fit the ropes before mounting the catapult onto a stand. Incidentally, this approach was used by the technicians on the television documentary 'Beat the Ancients': [http://www.channel5.com/shows/beat-the-ancestors/episodes/roman-war-machine](http://www.channel5.com/shows/beat-the-ancestors/episodes/roman-war-machine), although, unlike on the documentary, excess tension was not placed on the ropes, since any slack would be taken up during torsioning.

687 Heron, *Belopoeica* 98.6-99.2.

688 As above, this was learned from experience. The instability of the Roman catapult on its stand taught the operators to torsion the catapult at ground level; this also made it possible to reach the top and bottom washers more easily. However, this would not avoid the problems of having to torsion the catapult when it was fully built, since extra torsion might be needed later to manage the problem of power being lost during shooting.

689 For an example, see Fig. 40.

690 Heron, *Belopoeica* 101.10-102.1.

691 See Section 1 'Philon'.
catapult's structure and gave the whole structure some flexibility.

A hole was drilled on each side of the table, halfway up the side and at the front, where the table projected slightly from the spring-frame. The holes were large enough for thick cord to be passed through several times. Holes of the same size (16mm) were drilled on both of the side-poles of the ladder, immediately above those drilled into the table. They were off-set slightly from the mortices which held the rungs to avoid the potential problem of the wood splitting. Holes were also drilled at the end of the table projecting from the back of the spring-frame, of the same size and in equivalent positions, to allow the table and the ladder to be lashed together and to the spring-frame. This was important for two reasons: first, unless all three components were lashed together, the ladder was unstable and tended to move vertically; second, before lashing was added, as the slider was winched back the ladder was forced forwards by the torsion in the springs. Lashing the components together held the entire structure in place much more firmly.\textsuperscript{692}

Of the technical authors, only Vitruvius explains how the stone-shooting catapult should be mounted on a stand. However, Vitruvius' engine is of a considerably different design to the catapult described by Philon, especially with regard to the structure of the spring-frame.\textsuperscript{693} Therefore, while it is clear that the catapult must have had some sort of stand (otherwise, its missiles would have had a low, flat trajectory which would do little damage; it would also be impossible to add torsion to the bottom half of the spring if the bottom washers were resting on the ground), the type of stand which this catapult should have is unknown. Here, it was decided that trestles would be used to support the front and back of the engine; those at the back could be raised and lowered to adjust the catapult for shooting and would provide support to the ladder and to the spring-frame. They would also be easily transportable. Trestles which were bought off-the-shelf proved to be too flimsy for the weight of the catapult. Therefore, it was decided to use the trestles available in the

\textsuperscript{692}Figs. 42 and 45.

\textsuperscript{693}Compare Philon, \textit{Belopoeica} 53.8-54.15 and Vitruvius, \textit{De Architectura} 10.11.1-9. For a visual illustration, see Marsden (1969), 35 Figure 17, and Figure I.22.
workshop, which were generally used to support metal which was being welded or cut. As such, they were certainly strong enough to carry the weight of the catapult, and yet were light enough to be moved around easily.\footnote{Figs. 42-43.}

**Technical Conclusions**

Although Philon is the most technical of the authors considered by this thesis, there are gaps evident in his explanation of how to build this type of catapult. Most notably, the description of the ὑπόθεμα (‘counter-plate’) is lacking the necessary detail. In building the catapults many decisions had to be made on the spot, including methods for cutting, measuring, and finishing the many components. Where gaps in the treatise were found, and where the solutions to these problems could not be found in the other artillery manuals, more careful consideration was needed to find an appropriate solution. The methods by which the gaps were filled aimed to be as simple as possible, since more overly complicated solutions are more likely to stray from the original designs and intentions of the ancient engineers. It is particularly worth noting that the solution offered by this thesis for the construction of the counter-plate solves more multiple problems which have previously not been addressed, especially its ability to fix the outer-framework of the spring-frame together.

Overall, though, in building this catapult it was possible to follow Philon's construction notes thoroughly. His treatise does provide the vast majority of the information needed to build a catapult of this type. He provides a much higher level of detail than Heron, though where gaps do exist in the text, Heron can be an extremely useful source for comparison. Where Heron is lacking in detail, some aspects of Vitruvius' work are applicable to Philon's design, and can be adapted to suit this earlier stone-shooting catapult.
**Building Clytaemnestra**

**Calculating the dimensions**

It was first necessary to establish the dimensions of the components based on Philon's proportional system; it was also necessary to establish the components for which Philon gives no dimensions, and use other evidence to gauge their measurements. The proportional measurements were entered into a spreadsheet, just as for the stone-shooting catapult. As discussed above, it was decided that the bolt-shooter, *Clytaemnestra*, was to be a 3-cubit catapult with a spring-hole diameter of 7.5cm. This measurement was, therefore, entered into the spreadsheet and the other available dimensions were calculated.

**Building the spring-frame**

The first components to be constructed were the two hole-carriers. Their shape was simpler than those of the stone-shooting catapult. Philon notes that the hole-carrier widens at the middle, giving us the dimensions but not telling us whether the line between those points is straight or curved or whether the centre comes to a point or if it is flat. Heron's *euthytone*, however, has a curved edge, and so this shape which was initially chosen. Neither author tells us whether the increase in size comes at the front or back of the catapult. Marsden illustrates the *euthytone* with the curvature at the back of the spring-frame, though he does not explain his reasoning. Because there seemed to be some ambiguity as to the construction (and because the widths given for the stanchions were the

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695See above. Annotated diagrams can be seen in Figs. 90-92. Descriptions of all components may be found in the Glossary.
696See Appendix 1, Table 11.
697Philon, *Belopoeica* 55.4-5.
698Heron, *Belopoeica* 104.9-105.3.
699Marsden (1999), 57 Figs. 21 and 22 (Heron and Philon's arrow-shooting catapults), and diagram 10 (Vitruvius' Scorpion).
the layout of the hole-carriers in Vitruvius' *euthytone* catapult was used, with the side- and centre-stanchions aligned. However, after the hole-carriers had been constructed, a re-reading of Heron suggested (although his description of the component is by no means explicit) that the centre-stanchions should, in fact, be offset from the side-stanchions, thus explaining the difference in width at the centre of the hole-carriers. This gives the arms an improved range of movement, not needed in Vitruvius' catapult because of the development of curved arms. The construction of this catapult was therefore delayed significantly while the hole-carriers were rebuilt.

The construction of the incorrectly and correctly designed hole-carriers followed the same process. In placing the spring-holes on the hole-carriers, it was possible to follow a proportional scheme worked out by Marsden for the distances between the spring-holes and the tenons of the stanchions. His calculations take the measurements provided by Philon for the length of the hole-carrier, the two spring-holes, the widths of each of the four stanchions, and estimates the aperture at 1D, which makes sense in terms of balancing the symmetry of the spring-frame (although Vitruvius' aperture is only $\frac{1}{4}$D). This then leaves enough space for four gaps of $\frac{3}{8}$D, giving slightly more space than is required by the width of the washer, which makes sense since the flange around the washer must be accommodated. Lines were marked onto the wood in pencil to show these separations, and another line at $90^\circ$ to them marked the width of the hole-carrier, excluding the extension discussed above. The spring-holes were drawn centrally between the edge of the hole-carrier and the line excluding the extension in the spaces assigned to them.

The next stage was to cut out the mortices which would match the tenons on the stanchions, and to remove the centres of the spring-holes. The edges of the mortices

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700See Appendix 1, Table 11.
701Vitruvius 10.10.2. See Fig. 48. See also Marsden (1999), Diagram 10.
702Heron, *Belopoeica* 106.2-5. See Fig. 49.
703Contrast Marsden (1969), 21 Fig.10 and Fig. 11, and Marsden (1969), 201.
704Marsden (1999), 170 n. 72.
705Vitruvius, 10.10.3
706Fig. 49.
707For the size of these mortices, see the description of the construction below.
were drilled out using the pillar-drill, and pilot holes were drilled through the centres of the
mortices to guide broader drill-bits used with a hand-held drill. These removed most of the
wood from the centre of the holes, and the remaining wood was chiselled out, and finished
with the power-file. The spring-holes were cleared in the same way.

The two side-stanchions were built next. They were rough-cut to the appropriate
length (41.25cm, including the length of their tenons). After being planed, their other
dimensions\footnote{Width 11.25cm and thickness 4.69cm. See Appendix 1, Table 11.} were marked up and then cut. The tenons were then cut out at end of the
stanchions. To ensure that they were positioned evenly, the centre line (horizontally) of
each of the side-stanchions was marked, and half of the height of the stanchion, excluding
the tenons, was marked on either side. The thickness of the tenons then had to be marked
up, which it was decided would be just under half the width of the whole stanchion, at
5.5cm. The thickness of the tenons was also around half the thickness of the stanchion at
2.2cm. Philon and Heron do not specify the size or type of tenons to be used in the bolt-
shooting catapult.\footnote{Both authors mention 'double tenons' elsewhere in their treatises,\textsuperscript{710} but, as noted above, the construction of that type of joint was too complex to be practical. However, the use of either type of tenon should not affect the functioning of the mechanical components of the catapult, and was seen as unlikely to affect the engine's durability.\textsuperscript{711} It was decided to give the tenon such a large thickness as a safety precaution; being very thick, it would be less likely to snap under pressure. It was necessary to balance this with the risk of the wood surrounding the mortices fracturing because it was too thin. These risks were thought to be minimised by the fact that the pressure does not act along the grain of the wood for either the tenons of the stanchions or for the hole-carriers. A half-
and-half approach to the thickness of the tenons and the wood surrounding them in the
hole-carrier seemed a reasonable compromise.} The tenons were cut using the band saw. Two cuts were made at each side of the

\footnote{\textsuperscript{708} Width 11.25cm and thickness 4.69cm. See Appendix 1, Table 11.}
\footnote{\textsuperscript{709} Philon, \textit{Belopoeica} 54.25-55.11, and Heron, \textit{Belopoeica} 105.9. See also Marsden (1969), 28.}
\footnote{\textsuperscript{710} \textit{διτορμίας:} Heron, \textit{Belopoeica} 92.8 and 93.3, and Philon, \textit{Belopoeica} 63.15.}
\footnote{\textsuperscript{711} This was not the case, however. See below for more details.}
tenon, the first cutting horizontally across the top of the stanchion to the edge of the tenon, and the second cutting vertically along the line which showed the edge of the tenon. The centre of the width of each tenon was marked at several points down its height, and half of its eventual thickness was marked at either side. Lines were drawn connecting these points, and the two outer lines were cut out. The band-saw was then used again to cut in on the broad sides of each stanchion to remove the excess wood along the line marking the edge of the stanchion's height.

The centre-stanchions were simpler to construct. These were thinner than the side-stanchions at 2.8cm, meaning that they were already of a similar thickness to the tenons of the side-stanchions. Although the centre-stanchions take relatively little strain (being there to support the hole-carriers and the case), it was decided that to make their tenons any thinner would risk making them unnecessarily weaker. Neither Philon nor Heron gives any indication of how thick these tenons should be, and so it was decided to keep them at their full thickness for safety. The centre-stanchions were rough-cut and planed, and the positions of the tenons were marked out and then cut using the band-saw. The tenons and mortices were then fitted together through a process of trial and error; the edges of the tenons were neatened, and both the mortices and the tenons were sanded using the powerfile until they fitted each other tightly. Each mortice and tenon was marked with a matching letter, to avoid confusion on reassembly. Again, these letters did not follow any scheme set out by the ancient authors.\textsuperscript{712}

There were problems when fitting the centre-stanchions into one of the hole-carriers using this method. A split formed along one edge of and between the two centre holes when the tenons of the centre-stanchions were hammered into place.\textsuperscript{713} This at first appeared to be fairly minor; however, as the mortices were sanded further, a hairline crack emerged, running to approximately two thirds of the way through the hole-carrier. The gap

\textsuperscript{712}See above.
\textsuperscript{713}Fig. 53.
opened further when the centre-stanchions were hammered into position again, but contracted naturally when they were removed. Since the hole-carriers had already been rebuilt following the earlier mistake, it was decided that it would be better to try to work around the problem than to rebuild the hole-carrier entirely. The first attempt to fix the problem involved carefully filling the split with wood glue (PVA). However, this had to be done with the stanchions removed, to avoid their being stuck in the mortices, meaning that the crack was fully contracted when the glue was applied. As a result, the glue only entered the crack superficially and did not form a strong enough bond to prevent the crack from continuing to re-open.

The second approach was to remove the stress being placed on the wood altogether, by changing the fit of the tenons. It was thought that if the tenons were a slip-fit, rather than a hammer-fit, the stress on that part of the hole-carrier would be lessened significantly and the fracture in the wood might be less problematic. With this in mind, the mortices were sanded further. Care was taken not to sand the crack too much, in case that it should be further enlarged. The edges of the tenons were also carefully sanded to make them fit into the mortices more easily. Nevertheless, it was decided that these precautions were not enough to ensure that the spring-frame would not fracture completely under stress. By this point, another crack had developed at the edge a mortice which held one of the side-stanchions, and there was a risk that the thin wood at the edge could break off; it was therefore decided that the hole-carrier should be supported with an off-cut of wood and banded with iron plates instead.

These were manufactured from thin sheets, approximately 3mm thick, which were cut to match the size of each side of the spring-frame. They were then held in place and welded together whilst in position on the wood. This was risky, but necessary: the wood was scorched in a couple of places because of the heat, but had the plates not been held in

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714Figs. 50-51.
715Figs. 51-53.
position there would have been too great a risk that the joints would not match the corners of the spring-frame precisely. Holes were drilled into the metal, so that the box could be screwed onto the spring-frame away from the cracks in the wood. A box was also built for, and attached to, the other hole-carrier, to maintain the spring-frame's balance. This type of framework was used in the ancient world in both Greek and Roman engines. Philon specifically notes that this type of plating was commonly used to support weakened components (though he does warn against letting components reach the stage where they must be plated for support).

Another problem which arose because of the initial split in one of the hole-carriers was that it would have been very difficult to cut out the curve at the back of the hole-carrier recommended by Philon and Heron. The crack was positioned such that cutting anything from the back of the hole-carrier risked putting the wood surrounding it under strain, and possibly enlarging the break. The vibrations from cutting the wood, either using machinery or by hand, might have led to further damage. Therefore, it was decided that it was not worth the risk, especially as the curve seems to be cosmetic. It would also have been much more difficult to fit a curved plate to the supporting metal box than a flat one. The box which was constructed supported the hole-carrier effectively and was much more practical.

Parallels for this kind of plating exist in the archaeological record. The plating of the Caminreal catapult, which dates to around 75BC, survives, though it is of a more advanced design than Philon's version. It highlights the dangers noted in Philon's treatise of over-enlarging the spring-holes, with the result that the nails which fix the plating into

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716See e.g. Philon, Belopoeica 54.17-19 and Vitruvius, De Architectura 10.10.2. For archaeological evidence, see Bishop and Coulston (2009), 58-59 and 168-169, and Schalles' (2010) edited volume on the Xanten manuballistra, passim.
717Philon, Belopoeica 57.9-27.
718See above.
719Fig. 53.
721Rihll (2007), 179 notes that the washers are Vitruvian in design.
position have run into the spring-holes themselves and had to be hammered flat.\textsuperscript{722} The plating itself shows that the extension at the rear of the hole-carriers was constructed with straight, rather than curving lines; it also shows that the plating was overlapped where further plates were added.\textsuperscript{723} A large quantity of the iron plating survives, including plates which covered the hole-carriers, the side-stanchions (on three sides), and the centre-stanchion along with the washers, showing that almost the entirety of the spring-frame was be covered in metalwork.\textsuperscript{724} The plates on the upper and lower hole-carriers vary in their thickness, ranging from 78 to 80mm.\textsuperscript{725} Given that they suffered extensively from corrosion,\textsuperscript{726} it seems likely that they were originally much thicker. Nails which fixed the plates onto the woodwork were found with the other metalwork.\textsuperscript{727} The plating for the Ampurias catapult survives in two parts along with its washers and has been dated to the second century BC.\textsuperscript{728} Again, it shows that the rear of the hole-carriers were constructed with straight (as opposed to curved) lines.\textsuperscript{729} Like the Caminreal catapult, the Ampurias remains appear to have suffered from extensive corrosion.\textsuperscript{730} Interestingly, unlike the Ampurias catapult, the iron plating seems to have been fixed onto the catapult not with nails but with bars running through the entirety of the woodwork in the spring-frame.\textsuperscript{731}

Several important lessons can be learned from these problems. First, the amount of space left between the mortices and the edges of the hole-carriers was clearly insufficient. Should this model of catapult be built in the future, the tenons of the stanchions (in particular, the side-stanchions) should be made smaller to allow more wood to remain in place around the mortices. This would have to be a careful balancing act: the tenons should not be allowed to be too small, otherwise there would be a risk of cracks developing in

\textsuperscript{722}Rihll (2007), 153 and 153 Fig. 7.1 See also Philon, \textit{Belopoeica} 57.1-16.
\textsuperscript{723}Rihll (2007), 153 and 153 Fig. 7.1.
\textsuperscript{724}Vicente et al. (1997), 169-170.
\textsuperscript{725}Vicente et al. (1997), 170.
\textsuperscript{726}Vicente et al. (1997), 169.
\textsuperscript{727}Vicente et al. (1997), 169-170.
\textsuperscript{728}Bishop and Coulston (2009), 58-59.
\textsuperscript{729}Schramm (1980), 41 Abb. 14
\textsuperscript{730}Schramm (1980), 40-42, 41 Abb. 14, and 42 Abb. 15.
\textsuperscript{731}Schramm (1980), 44-45, 44 Abb 16, and 45 Abb. 17. See also Bishop and Coulston (2009), 59 Fig. 28.
them, or that they might themselves break off under the force of being hammered into position.\textsuperscript{732} Second, double tenons would be a good way to avoid this type of problem, since if a crack were to develop next to one mortice, there would be a back-up in place to prevent the split from causing a major problem. Third, the question of how best to store the wooden components is raised. Here, the wood was kept in an unventilated shipping container, at a time when the external weather conditions fluctuated greatly. The temperature in particular was very variable. Such conditions are known to lead to wood cracking, and despite the fact that seasoned wood was used in this project the variability of weather conditions probably played some part in the splits developing (though it is possible that there was a flaw in the wood to begin with). To help prevent problems like this in the future, regular treatment of the wood with linseed or olive oil is recommended. Ventilation holes were cut into the side of the shipping container (connecting to another enclosed area) to remove some of the problems associated with rapid and frequent changes of temperature, by regulating the humidity within the storage space, thus keeping the wood in better condition.

**Building the case, slider, trigger mechanism, and winch**

The case and slider were constructed together, because they form a dovetail joint between the case and the runner at the bottom of the slider.\textsuperscript{733} Three beams were cut, each 120cm long. Philon does not give the overall height of the case and slider, though Vitruvius gives a figure of 1D for the case and 0.75D overall for the slider.\textsuperscript{734} In any case, the missile must be shot from approximately halfway up the spring-frame to allow equal forces to be exerted on it,\textsuperscript{735} and so it was decided to make the height of the case and slider together

\textsuperscript{732}For this as a real possibility, see Section 2 'Building Medusa - Building the table, ladder, slider, and winch' above.
\textsuperscript{733}Heron, *Belopoeica* 85.7-10. See also Fig. 30.
\textsuperscript{734}Vitruvius, *De Architectura* 10.10.3 and 10.10.4 respectively.
\textsuperscript{735}See above.
13cm. The three beams which were cut had a thickness of approximately 4.5cm, and were planed down to give the overall thickness specified. The width of the components was easy to calculate, since the size of the aperture was known to be 1D (7.5cm).\textsuperscript{736} The case and slider would logically be of the same width as the aperture to allow them to fit tightly into the spring-frame. The slider should be substantially shorter than the case, though Philon does not provide a measurement. If the slider were the same length as the case, it would project an extremely long way when the missile was loaded, which would risk damage to the component or the rest of the catapult should it fall out or topple the engine. Moreover, it would be more vulnerable to attack since it would project further than necessary from the spring-frame. Therefore, it was decided to use Vitruvius' recommendation for the length of the slider, which comes to 16D (120cm).\textsuperscript{737} One piece, to serve as the top of the slider, was cut down to this length.

The next stage was to form the dovetail, as described by Heron in his section on the early torsion frames.\textsuperscript{738} It also forces the slider to conform exactly to a fixed path as it is pushed forwards before shooting and winched backwards during use. The male part of the joint is fixed to the underside of the slider, and the female part is fixed to the upper side of the case, forming the case's side. Unlike fixed dovetail joints which can be difficult to construct accurately, this moving joint is simple to make. The blade of the small table-saw can be set to any angle up to 30° from vertical. It is therefore possible to set it to an angle (in this case 20°) and to use two cuts to make both the side pieces of the case and the runner of the slider from a single piece of wood.\textsuperscript{739} This angle was the only practical one to use, since had the angle been any more acute the cuts would have taken up too much of the wood; had the cuts been steeper, the side pieces would have been too narrow to stop the slider lifting during operation.

Having cut the angled pieces, it was necessary to cut the runner to length to match

\textsuperscript{736}See Appendix 1, Table 11.
\textsuperscript{737}Vitruvius, \textit{De Architectura} 10.10.4
\textsuperscript{738}Heron, \textit{Belopoeica} 85.8-10.
\textsuperscript{739}Fig. 54.
the top of the slider. The side-pieces were fixed to the upper side of the case using wood glue, again PVA. Given how thin the bottom edge of the side-pieces was, it was decided not to risk splitting the wood by drilling into it or by hammering in nails, since problems had already been encountered with cracks developing. Likewise, the runner was glued into position. In order to ensure that the glue dried with the runner and side-pieces positioned precisely, they were clamped and left to dry. Problems were anticipated with this approach, however. The glue was strong along the length of the wood, but across the wood the join was relatively weak. At one point later in the building process, the runner of the slider was detached from the upper part of the slider unintentionally and had to be glued back into place. In operation, though, forces would act on the length of the slider, not come from the side. Moreover, from a safety perspective, should the slider break while the catapult was in operation, then a ratchet system would be in place as a backup. In testing, no problems were encountered.

A groove to direct the missile and in which it could rest before shooting was cut next using the router, with the slider held in a vice to keep it steady. A line was drawn down the centre of the top of the slider, with parallel lines marked on either side to show the maximum width which had been decided. Based on the bolt-heads which were being used, the size and diameter of the missiles' shaft had already been determined, and the width of the groove (being 1.5cm) was designed to accommodate this. The rear end of the slider was marked off for the trigger mechanism so that the groove would not be cut there. The same router bit was used as above.

The trigger mechanism was built at the same time as the one for the stone-throwing catapult, and the welder who constructed the boxes for the trigger mechanisms misread the instructions for both. Again, the box ended up with external dimensions which should have

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740Fig. 54.
741See above.
742See below.
743See Section 2 'Missiles' below.
744See Section 2, 'Building Medusa' above.
been the internal dimensions, and the wooden components had to be adapted to match. The result was less dramatic than had been the case for the stone-shooting catapult, and only a small part of the back of the slider had to be removed by sanding. The trigger mechanism was constructed slightly differently to that of the stone-shooting catapult, partly because the box could be made with a greater height, and partly because the bolt-shooting catapult needed a split trigger rather than a simple bent bar. Since the component to which the trigger would be fixed was larger, the box for the bolt-shooting catapult eventually measured 9cm by 7cm by 4.5cm. Like the trigger mechanism for the stone-shooting catapult, though, two upright metal bars, measuring 4cm by 4cm by 1cm, were welded to the front of the trigger box. These had a hole drilled through two-thirds of the way up to accommodate the bolt which held the trigger bar. A hole was drilled at the back left hand corner, through which the bolt which held the releasing bar could be fastened. Another hole was drilled through the right hand side of the box, halfway up the side, through which a bolt could be placed to support the ratchet pawl. Further holes were drilled to allow the trigger box to be screwed into place. The heads of the bolts to support the trigger release and the ratchet pawl were welded to the inside of the trigger box; because there was some projection of the heads of the bolts as a result, the slider had to have some sections chiselled away to accommodate them.

The ratchet system copied that of the stone-shooting catapult very closely, and differed only in the overall length and width of the toothed section (77cm and 1.8cm respectively), and in the dimensions of the pawl (which had a length of 14.5cm, a thickness of 0.7cm, and a width of 3cm). An angle was cut at one end of the pawl to allow it to grip into the teeth. The height, length, and angle of the individual teeth, and the angle at which the pawl was cut, were the same as those of the stone-thrower. The material from which

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745 Philon, again, does not describe the type of trigger. However, Vitruvius' description of the trigger as a 'claw' (*epitoxidos* or *manucla*; the Greek word *σχαστηρία* is also used, although this is an emendation) indicates a split bar. Vitruvius, *De Architectura* 10.10.4. See also Heron, *Belopoeica* 111.1-6.
746 Fig. 57.
747 See Section 2 'Building Medusa' above.
the teeth were made was different: it had been anticipated that, as this was a smaller catapult, narrower wood could be used and a pine plank was judged to be sufficient.\textsuperscript{748} However, in practice it was established that the wood needed to be much thicker, and so another plank of pine was glued on top of the original plank. The toothed part of the ratchet system was glued into place (out of concern that screws or nails could lead to the wood splitting). A gap was left at the back of the slider for the winch.

It was then realised that the wooden beam forming the bottom of the case was too thin to hold the axle of the winch mechanism,\textsuperscript{749} and that an adaptation to the design set out by Philon was needed. The axle chosen was a thick hardwood dowel 16mm in diameter, for the same reasons as set out in the case of the stone-shooting catapult.\textsuperscript{750} There was also a problem in that there was not enough space in the channel through which the slider ran for the rope from the winch mechanism to be wound up, since the gap was very narrow. The solution to both of these problems was to adapt a design given by Vitruvius for his bolt-shooter. He recommends that the catapult builder should add 'cheek-pieces' (\textit{bucculas}) to the back of the case, which project behind and parallel to the side-pieces of the case.\textsuperscript{751} These leave a gap behind the case which can be used to allow the rope from the winch to be wound up as the catapult is operated, and provide a substantial support for the axle and winch. It was decided to build the cheek-pieces to the same height as the case, both for appearance's sake and to ensure that there was plenty of wood surrounding the axle. The height of the cheek-pieces in Vitruvius' design also matches the height of the case.\textsuperscript{752} Since there was a suitable off-cut of wood available, and there was no guidance from Philon, it was decided to make each of the cheek-pieces measure 22.5cm by 4cm by 6.5cm. These measurements were entirely arbitrary, but since this would not affect the functioning of the catapult in any way it was decided that these measurements were viable. The single block

\textsuperscript{748}Fig. 58.
\textsuperscript{749}For details of which, see below.
\textsuperscript{750}See Section 2 'Building Medusa' above.
\textsuperscript{751}Vitruvius, \textit{De Architectura} 10.10.2.
\textsuperscript{752}See above.
of wood was sawn in half. A hole was drilled through the two cheek-pieces, which were held together in a clamp, using the pillar-drill. The drill-bit was 2mm wider than the axle, at 18mm, to ensure that the axle would be able to move freely whilst remaining supported. The cheek-pieces were then glued into position, with the axle running through the holes to ensure that they lined up properly, using PVA. The whole assembly was clamped and left to dry. Once again the risk of the wood splitting made it unattractive to use screws or nails.\textsuperscript{753}

The winch drums were constructed in exactly the same way as those for the stone-shooting catapult.\textsuperscript{754} A piece of ash measuring approximately 30cm by 30cm by 10cm was planed smooth. The outline of the winch drum, with a diameter of 18.75cm,\textsuperscript{755} was drawn onto it using compass and pencil, then redrawn in permanent marker for clarity. The block was then sawn in half, as above. Even when the block had been fully cut through, the pieces were difficult to separate, as a result of the toughness of the ash. In the end, the only way to separate the pieces was to use wedges and chisels to force the block apart. The rough sides were planed smooth, and then the winch drum was marked up on the second half of the block. The circles were then cut out and the edges sanded slightly. The centre of each of the drums was then marked and drilled out using a 16mm drill-bit. Four holes at 90° to each other were then drilled into the sides of each winch drum so that a handle could be used to turn the winch. Finally, the axle was hammered through the winch drums and the winch was fitted to the case through the cheek-pieces.

\textsuperscript{753}Figs. 55-56.
\textsuperscript{754}Figs. 34-35.
\textsuperscript{755}As in the case of the stone-thrower, this measurement was taken from Vitruvius' suggestion: Vitruvius, \textit{De Architectura}. 10.10.5.
Powering the catapult: the washers, arms, and bowstring

As discussed above, the washers were constructed from steel pipe. For this catapult, they had an internal diameter of 7.5cm, an external diameter of 9.5cm, and a height of 5.6cm.\textsuperscript{756} Flanges, with an overall external diameter of 12.5cm, an internal diameter matching the external diameter of the washers, and a thickness of 1cm, were welded onto the washers 1cm from their bases. Each of the flanges had sixteen holes drilled through, spaced evenly. As above, this number is greater than that shown in the archaeological record. Again, this was designed to allow more accuracy and a greater degree of fine tuning, though as noted above this was not required once the catapults were fully torsioned.

The bottom washers were made to the same measurements as the flanges but with half the number of holes, again evenly spaced. Rather than drilling additional holes to screw them into place, unlike the stone-shooting catapult, four of the holes in the bottom washers were countersunk to allow screws to be positioned where they would not affect the top washers' movement. They were then fixed into place very carefully, to avoid further splitting the wood of the damaged hole-carrier. The position of the screws in this hole-carrier was crucial, because they had to be placed well away from the fractures; however, the design and size of the washer and hole-carrier limited how they could be placed. Pilot holes were drilled to make the placement of the screws as safe as possible.\textsuperscript{757}

Levers were next attached to the upper parts of the top washers to make it possible to rotate them and supply power to the rope-springs. Steel bars were cut according to the dimensions recommended by Philon for his stone-thrower, since none of the writers gives dimensions for those of their bolt-shooting catapults.\textsuperscript{758} Because of the change in proportional sizes of the spring-frame, only the height and thickness (each 1.5cm) were of use. The length was determined by the maximum which would work in practice, which

\textsuperscript{756}This dimension follows Marsden's suggestion for a figure which Philon chooses not to include in his list of dimensions: Marsden (1969), 44 and Marsden (1999), 266.
\textsuperscript{757}Figs. 51 and 53.
\textsuperscript{758}Philon, Belopoeica 53.23-24.
was established as 23cm. There were two reasons behind the decision to make the levers as long as possible: first, the dimensions for the tuning tool had not yet been decided, and so it was thought best to give the largest size possible with which it could be engaged; second, it is easier to grind down a long bar than to add length to a shorter bar, and a bar with added length can be weaker structurally than an one which has not been lengthened. Grooves were ground out of the upper side of the top washers to a depth suitable for welding and the bars were welded onto the washers across their centres.\textsuperscript{759}

Like the arms for stone-thrower (and unlike their later Vitruvian counterparts),\textsuperscript{760} those recommended by Philon are straight,\textsuperscript{761} and thus relatively simple to construct, though Philon does not give us their actual dimensions. Therefore, the measurements used by Vitruvius were adapted, so that the overall length (though not the curvature) which he recommends were used, but it was decided to use the mean of the two thicknesses which he suggests.\textsuperscript{762} The arms were trimmed to just over this thickness (3.5cm by 3.5cm), and were then planed to size. When the catapult was fully assembled, grooves were cut into the arms approximately 4cm from the outer end to help the bowstring remain in position.

The design and construction of the bowstring was slightly different for this catapult, since neither author gives the length of the bowstrings. Moreover, because of the different proportional system, the length given for the stone-shooter could not be applied here. Therefore, the length of the bowstring had to be established theoretically. It was decided to make the bowstring the maximum length it would need to be for the slider to be drawn back fully; if this were overlong, the bowstring could be twisted to shorten its length. The

\textsuperscript{759}Visible in Figs. 61-62.
\textsuperscript{760}The curved arms in the Vitruvian bolt-shooter allow for a greater angle of movement (35° in Philon's catapult as opposed to 47.5° in Vitruvius' bolt-shooter) – see Marsden (1969), 21 Fig. 11 and Marsden (1999), 230 Fig. 12a respectively. The allows more of the potential energy in stored in the springs to be released once the bolt is loosed; in effect, the slider can be withdrawn further in the later catapult. Experience of shooting a reconstructed Roman catapult, \textit{Alecto}, suggests that the limbs could be flexible depending on their method of manufacture. The effect is comparable to the way in which a composite bow works in action, but the construction is different (with no use of sinew or horn in the process) and the curve of the limbs is more pronounced – see Vitruvius, \textit{De Architectura} 10.10.5. See also Wilkins (2000), 91.
\textsuperscript{761}Philon, \textit{Belopoeica} 55.9.
\textsuperscript{762}In Vitruvius' bolt-shooting catapult the curved arms have a variable thickness which changes from 7/16D at its thinnest to 9/16D at its thickest: Vitruvius, \textit{De Architectura} 10.10.5.
lengths of the arms were added together with the width of the case; this gave a measurement of 110.5cm, and was much more suitable for the task at hand. Once again a bowstring jig was used to construct the bowstring, and the material used was dacron. This was done in the same way as for the stone-shooting catapult, though the loops at each end of the bowstring were smaller, because of the narrower arms.  

Building the stand

Philon does not describe how the catapult should be mounted. Therefore, it was decided to use the type of stand recommended by Vitruvius, which is broadly similar to that recommended by Heron for his bolt-shooting catapult, including the use of a universal joint to allow the catapult to be moved horizontally and vertically.  This is one of the rare instances where Heron gives a specific measurement for a component, suggesting that the pillar of the stand should be 1.5 cubits high (69.36cm). Vitruvius' proportional measurement for the height of the stand (12D) gives the main column of this catapult a height of 90cm. It was decided to use Vitruvius' measurements partly because of the proportional system (allowing the stand to remain proportionate to the catapult). Moreover, in practical terms, 90cm was seen as a better operational height, given the heights of those who would be operating the catapult during the testing phase.

The stand consists of an upright column (in this case measuring 90cm by 5.63cm by 5.63cm), with (according to Vitruvius' initial phrasing) a single joist through which the column is fixed by means of a tenon as its base.  However, such a system leads to the catapult being unstable, and Marsden interprets the base of the stand as consisting of a

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763 See above for more detail. See also Figs. 39-40.
764 Vitruvius, De Architectura. 10.10.4-5. Heron, Belopoeica 86.4-90.2 (for the use of a universal joint, see specifically 89.6-8).
765 ὕψος ἔχων πῆχος ἑνὸς ἡμίσους: Heron, Belopoeica 88.2-3.
766 Vitruvius, De Architectura. 10.10.4
767 Vitruvius, De Architectura. 10.10.4: columnellae basis in solo foraminum octo, latitudo in plinthide, in qua statuitur columnella, foraminis S°, crassitudo ΤZ. (NB: the Vitruvian symbol used here 'S°' = ¼. See Marsden (1999), 187, quoting Schramm (1917), 719).
cross made up of two of these joists.\textsuperscript{768} A further reason to accept Marsden's interpretation is that the stand has three legs, identical in all dimensions,\textsuperscript{769} with a single beam acting as the base of the stand, either one or two of these legs would not reach the ground and would, in effect, be useless unless the legs were moved further down the column. However, the dimensions for the legs are relatively slender. While they might support larger machines reasonably well, as a result of the proportional measurements, they would be too weak to support smaller engines. Since the engine's stability is very important, both for safety reasons, to avoid damage to the catapult and to help with the aiming of a shot, it was decided to accept Marsden's interpretation.

First, the column was cut to 90cm in length (with an extra 11.25cm allowed for the tenon) and planed to make the thickness and width 5.63cm each. It was decided that, to ensure that the tenon was sturdy enough to carry the weight of the column, it should measure approximately \(2.5cm^2\). This dimension was measured onto the wood, along with the tenon's overall length, and the tenon was cut out and then neatened with the power-file. The base of the stand was constructed by cutting out and planing two planks as closely to Vitruvius' dimensions as possible (60cm by 4.69cm by 5.63cm). If the measurement for the tenon given by Vitruvius is correct (a length of 1.5D, equivalent here to 11.25cm), the planks would need to lie on top of each other for the tenon to fit; this would be unwieldy and unbalanced, unless blocks (not mentioned by Vitruvius) were placed under the upper plank. Again, the problem would arise of at least one of the legs not reaching the base properly, or having to be moved further down the side of the column in order to reach the base. Therefore, to improve the base's stability, it was decided to reduce the length of the tenon and overlap the planks of the base. At the centre of each plank, a channel half the thickness of the beams and equal to their width was cut and the excess wood removed using chisels. The beams were overlapped to form a cross, and the centre was marked with

\textsuperscript{768}Marsden (1999), 196 and Diagram 10.  
\textsuperscript{769}Vitruvius, \textit{De Architectura}. 10.10.4: \textit{eius capreoli tres, quorum longitudo foraminum VIII, latitudo dimidium foraminis, crassitudo Z.}
the tenon's width and thickness. The corners of the resulting square were drilled and the excess wood was removed by chiselling and sanding. The centres of the beams were glued and clamped. The tenon was shortened to match the new thickness of the base, and the sides of the tenon were also glued and fixed to the base.

The legs were next cut to length and planed to the correct size (67.5cm by 3.75cm by 3.28cm), though they were left somewhat overlong so that they could be fitted to the stand. Fitting the legs was a two-person task; one person held the legs up against the column and base, while the other marked angles to which they needed to be cut. These were then cut, and each leg was nailed into position. There were some problems with this approach, mainly that the wood tended to split around the nails. To prevent further damage the legs were oiled with olive oil to reduce the risk of other splits developing. 770

The rear end of the stand was constructed next. The cross-piece, the dimensions for which Vitruvius gives (in this case) as 5.63cm by 7.5cm, was cut and glued into position just above where the legs met the column, on the side where no leg was present. 771 When the glue had set, it was reinforced with a steel bracket which was fixed onto its upper side. The 'stay' (90cm by 5.63cm by 4.69cm) was then fitted to the cross-piece just as the legs were fitted to the column. It, too, was glued into position and nailed into place. The final component was the 'rest', a moveable upright beam on which the case rests when being loaded. This had the same width and thickness as the stay, but was shorter, at 60cm. To allow the rest to move down and away from the case during the catapult's operation, the rest was cut to match the angle of the stay and joined to it by a long hinge which was screwed onto both components.

One important adaptation was made to the design of the wooden part of the stand. In building a stand previously for a Roman catapult, it was discovered that the rest tended to sway while the case rested on it, and it was not providing a stable platform. Therefore, to

770 Fig. 59.
771 Fig. 60.
support the rest and to prevent it from moving sideways during operation, two small rectangular pieces of pine were glued to the stay on either side of the rest, with about half of their height projecting upwards. These were then glued, clamped, and left. They provided a small but effective support to prevent the rest from moving in a direction other than that upwards and downwards.

Finally, the universal joint was constructed. Vitruvius only tells us the height of this component (2D, or 15cm here), but the other dimensions can be established by examining the components to which it is being connected. We know from Heron that the universal joint has a pin which runs through the case, and so this tells us that the overall width of the universal joint must exceed, at least slightly, the width of the case. Therefore, the width of the universal joint for this catapult must be, at the smallest, 7.5cm, with at least 2mm added on either side to allow the case to move. The length of the universal joint is relatively unimportant; it needs only to be sufficient to support the pin which runs through it. Equally, the length of the prong which runs underneath the universal joint, allowing the catapult to be rotated horizontally, is not crucial, so long as it is at least enough to support the weight it carries. This factor is influenced as much by the hole drilled into the main column of the stand into which the universal joint is set. This hole must be as close to the diameter and length of the prong as possible, whilst still allowing it to rotate. It was decided, then, to give the overall dimensions of the universal joint for this catapult as follows: its height was 15cm, its width was 8cm, its length was 7cm, the the prong's length was 10cm, and its diameter was 1.5cm. The diameter of the pin which ran through the case was 8mm; this was judged to be sufficient to support the catapult, while being narrow enough that there was plenty of wood on either side of the hole drilled for it for safety.

Three steel plates with a thickness of approximately 3mm were welded together as the basis for the universal joint. The two side plates measured 15cm by 7cm, and the bottom plate measured 8cm by 7cm. A hole 8mm in diameter was drilled through the side

772Heron, *Belopoeica* 89.6-8.
plates at the centre three-quarters of the way up. The prong was then welded to the centre of the bottom plate. A hole was then drilled into the main column of the base, with a diameter of 18mm. The depth of the hole was much harder to gauge, because it needed to be deeper than the length of the depth-stop on the hand-held drill. The only way to check that the hole was deep enough was to drill a short distance and test the depth by putting the universal joint into the hole, before repeating the process. The final stage was to drill a hole to match the pin through the bottom of the case. This was a particularly delicate task because the hole needed to be drilled perfectly straight, otherwise the whole assembly would lean to one side. The hole was therefore drilled using the pillar-drill rather than the hand-held drill, to ensure that as much precision as possible could be exercised. The positioning of the hole was also important, since it needed to be as close the the spring-frame as possible to keep the catapult balanced, while being far enough away from the spring-frame that the maximum rotation of the assembly could be achieved.\textsuperscript{773}

**Assembly**

The assembly of the bolt-shooting catapult was much simpler than that of the stone-shooting catapult, and could be completed by one or two operators. The spring-frame was the first component to be assembled, with the stanchions being hammered into place on the hole-carriers. Having put the washers in place, the next stage was to fit the spring-ropes. Once again, this was done with the spring-frame face-downwards on the floor.\textsuperscript{774} Each spring needed approximately 30m of rope. One end of the rope was tied to the lever of the top washer on the catapult's upper side. The rope was then passed through the two washers, passing over and under the levers of each on every pass, until the spring-hole was as full of rope as possible. As with the stone-thrower, the process was that recommended by

\textsuperscript{773}The universal joint is visible in Fig. 61. 
\textsuperscript{774}See above.
Finally, the arms were slipped into the centre of the rope-springs and the bowstring was fitted. The rope-springs were torsioned just as the stone-shooter's were; however, because of the difference in the size of the two catapults' washers, a new torsioning bar had to be manufactured for this engine.

The spring-frame then needed to be fitted to the case and slider. The slider had already been pushed into the case. There were two problems associated with fitting the case and slider into the spring-frame. First, the fitting needed to be loose enough that the slider could run backwards and forwards easily; however, as the case and slider were the same width, it was impossible to make the case fit tightly, but not the slider. Second, something was needed to hold the case and slider at the bottom of the spring-frame: with nothing to limit the case and slider assembly, the only way to fit them was at the very top of the spring-frame, which would clearly be unworkable. Therefore, two narrow blocks of wood, the same length as the width of the centre-stanchions, were glued to the inside of the centre-stanchions, where the top of the slider should be when fitted correctly. When the slider was put in place the next morning, a small gap of approximately 5mm was left underneath the case, which needed to be filled in order for the case and slider to be firmly connected to the spring-frame. Therefore, two thin wedges were manufactured from offcuts of wood, which were hammered into place and made the fit as tight as possible. The whole assembly was then placed on the stand.

At this stage, however, it became apparent that this arrangement would not allow the slider to be operated since the pressure holding the catapult together would not allow it to move forwards or backwards. Two solutions to this problem were considered. First, the case could be fixed to the centre stanchions by means either of pegs or screws, with the wedges left underneath to support it. This solution was rejected to avoid splitting the wood of the case. An error in positioning, too, could affect the movement of the slider. Therefore, the second option, which involved removing 1.5cm from either side of the top of the slider

Heron, *Belopoeica* 98.6-99.2.
and moving the narrow blocks of wood which had been glued to the stanchions downwards (to push against the top of the case), was chosen. The blocks were carefully chiselled off the stanchions and sanded to remove the remaining glue using the power-file. They were then repositioned and glued.\footnote{776}

The removal of wood from each side of the slider presented greater difficulties. The trigger box was permanently fixed in place because the head of a screw which fixed it into place was ground off during the early testing phase (see below), and so could not be removed to allow the top of the slider to be trimmed. Cutting also risked damage to the slider's runner. Therefore, the slider was clamped onto the workbench with the side to be trimmed. Cuts 1.5cm deep were made at short, regular intervals along its length. The wood was then removed by hand using a chisel and then sanded. The fit was then checked by assembling the catapult.

**Technical Conclusions**

Philon's treatise contains the majority of the information needed to build this catapult, but the details can be difficult to interpret. In comparison to the amount of attention he focuses on the stone-shooting catapult, the space in his treatise dedicated to the standard bolt-shooter is tiny (approximately half a paragraph in Marsden's edition, compared to approximately two and a half pages for the stone-shooting catapult). The impression which can be gained from the text is not that Philon is deliberately omitting relevant details, but that the gaps which appear in his work arise from an assumption that his readers would already have a basic understanding of what the components would look like and how they would fit together. Most of gaps (e.g. the shape and positioning of the curve on the hole-carriers, and the size and construction of the stand) do not affect the functioning of the catapult itself and can be left to the engineer's individual judgement.

\footnote{776See Fig. 65.}
However, the description of the basic bolt-shooting catapult does stand in stark contrast to his extended criticism of this standard engine and the description of the benefits and construction of wedge-engine which follows it. This could be taken as a nudge by Philon to persuade his readers to use his own innovative design rather than the more simple and generic version, but does not remove the value of the information about the basic bolt-shooter which he does provide for his readers. It is possible that further details of the construction were contained in the original version of the treatise and were lost at some point during the text's transmission; how likely it is that this happened is impossible to judge based on what we have of the manuscript tradition. However, as a result of these gaps much more of the process of building this catapult was subject to trial and error, and thus more mistakes were made and corrected.

The most critical mistakes made in the construction of this catapult involved the hole-carriers. The first mistake was in a misunderstanding of the layout of the hole-carriers, and resulted in the first pair being scrapped entirely. The second was in using single, rather than double, tenons in the construction of the spring-frame. While this did not lead directly to the splitting of the wood, the problems created by the split would have been less had two smaller tenons been used. However, double tenons would have been much more complicated to construct (since it would require more cuts to the tenons, more drilling and chiselling for the mortices, and a much more precise placement of each).

The gaps in Philon's work on the bolt-shooting catapult need to be supplemented by the information available from Heron and Vitruvius to a much greater extent than his description of how to build the stone-shooting catapult. As a result, the catapult is perhaps best thought of as a combination of the three authors' designs. The crucial part – the spring-frame – is entirely described by Philon, though, which means that in terms of power and operation, this catapult is as close to the original design as possible.

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777Philon, Belopoeica 56.16-58.35.
778Philon, Belopoeica 59.1-67.27.
Missiles

This chapter will describe and explain the ways in which missiles were manufactured for both catapults, and which type and sizes of ropes were used for the spring-coils. The choice of rope is dealt with in a single section which discusses both engines, since the question of which type of rope to use applied equally to the bolt- and stone-shooting catapults. The manufacture of the missiles for each catapult will be dealt with in two separate sub-sections because of the different processes involved in each case.

Medusa

It was decided early on in the project not to use actual stones for ammunition for several reasons. First, natural stones, even those of similar size, shape, or weight may not be aerodynamically similar. Moreover, where stones are shaped by hand, the process can be long, drawn out, and expensive: Wilkins had a 'one-talent (26.2 kg) limestone ball' carved by a sculptor, and he admits that the process took 'two and a half days'.

It seems highly unlikely that the ancient catapult operators resorted to this level of perfectionism in the manufacture of their missiles: it would be incredibly wasteful to shoot something which took so long to manufacture in the general direction of the enemy, where it could potentially be reused (especially if it failed to hit its target). However, as discussed above, the presence of carved stone balls in various locations around the Mediterranean has suggested that catapults were in use prior to 399BC. These stones, weighing

780Wilkins (2003), 61 (this was done in preparation for the ‘Building the Impossible’ documentary).
781See Introduction.
782Rihill (2007), 29-30. Current thought holds that these stone balls were thrown or dropped by hand, rolled downhill, or pushed over walls onto attacking forces, rather than shot from catapults. Thrown stones also appear on two Neo-Assyrian palace reliefs, including reliefs from the North West Palace - British Museum number 124555: http://www.britishmuseum.org/research/collection_online/collection_object_details.aspx?objectId=367047&partId=1&searchText=neo-assyrian+reliefs&page=1 and British Museum number 124563: http://www.britishmuseum.org/research/collection_online/collection_object_details.aspx?objectId=367035&partId=1&searchText=neo-assyrian+reliefs&page=1. Images of thrown stones also appear on the Nereid monument from Xanthos – Rihill (2007), 11, and British Museum number
'between 2.7 and 21.8 kilograms'\textsuperscript{783} were found at Old Paphos in part of the 'siege mound apparently built by the Persians'.\textsuperscript{784} These rocks are very roughly round, with curved sides (and occasionally curved upper surfaces) and with flat bottoms.\textsuperscript{785} Found in the siege ramp built by the Persians in the early fifth century, the rocks from Paphos have been described as 'stone-missiles'\textsuperscript{786} It has been thought that these stones might have been thrown against the walls of the city by Persian catapults,\textsuperscript{787} but this view has since been discredited.\textsuperscript{788} However, the fact that these balls have been found implies that some in the ancient world were prepared to take a great deal of trouble over what were essentially disposable weapons – though in the case of the Paphos stones, the carving is so irregular as to make any shot taken with them highly unreliable, since their shapes make them likely to tumble or fly in an unpredictable direction.\textsuperscript{789} Moreover, examples of stone shot from the Roman period appear to have been roughly shaped to particular calibres in order to be used in catapults,\textsuperscript{790} and 'local sandstone' was used to manufacture stone shot of between one and ten \textit{minae} calibre at Numantia.\textsuperscript{791} Clay shot has also been found in a Roman context.\textsuperscript{792} However, without experience in shaping stones, and without a supply of the right shape and size available, it was impractical to use stone shot. Without access to a kiln, or any experience in manufacturing ceramics, it was also impossible to create clay shot. Both could have been commissioned, but this was precluded by their cost, especially given that clay shot could be expected to shatter when it hit the target or the ground. The sheer

\textsuperscript{785}Maier and Karageorghis (1984), 196 Fig. 185.
\textsuperscript{786}Maier and Karageorghis (1984), 197.
\textsuperscript{787}Maier and Karageorgis (1984), 200. See also Rihll (2007), 29.
\textsuperscript{788}Rihll (2007), 29-30. See also Pimouget-Pedarros' highly detailed and extensive re-examination of this issue based on the available archaeological and literary evidence: Pimouget-Pedarros (2000), 5-26.
\textsuperscript{789}Maier and Karageorghis (1984), 196 Fig. 185.
\textsuperscript{790}Bishop and Coulston (2009),58-61 and 89.
\textsuperscript{791}Bishop and Coulston (2009), 58.
\textsuperscript{792}Bishop and Coulston (2009), 89.
quantity of missiles which could be required in the testing phase, therefore, ruled out the possibility of commissioned missiles.

It was decided, then, that the most readily available material which could be worked by someone with little experience was concrete, as unmixed concrete is both cheap and easily obtained. Moreover, given that the weight of the concrete missiles was equal to the calibre of the catapult, there should be no difference in the missiles' performance as compared to stone shot. According to Philon's method for calculating the calibre of the missiles which this catapult can use, given that the diameter of the washer is 10cm or 5.2 dactyls (rounded up), is 545.75g or 0.9lb (i.e. 125 e, or 1.25 minae). The concrete balls themselves weighed approximately 600g or 1lb 6oz, only slightly heavier than the intended missile weight, making concrete an ideal material from which to make large quantities of disposable missiles cheaply. Moreover, by using a mould and the same mix of concrete each time, it was possible to make the missiles as consistently shaped as possible, which is highly desirable in experimentation of this kind, since the experiments carried out need to be repeatable. The mould used gave the missiles a diameter of 10cm, which easily fitted into the 12cm gap between the side-poles of the ladder.

In total, sixty concrete balls were made using this method, with forty being made with the three-to-one ratio of sand to concrete, and the remainder with a ratio of five-to-one. Such a large volume of missiles was manufactured because it was expected that a relatively large proportion of these would shatter or crumble after being shot through the catapult one or several times.

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793For conversion rates, see Marsden (1999), xvii-xviii. For the formulae, see Philon, Belopoeica 51.15-27 and Marsden (1999), 157.
794Fig. 65.
**Clytaemnestra**

We have a great deal of archaeological evidence concerning the design and construction of catapult bolt-heads.\(^{795}\) However, as Bishop and Coulston note, there can be difficulty in distinguishing between bolt-heads and arrowheads, or even spearheads.\(^{796}\) The manufacture of bolt-heads is described in detail by Sim and Ridge,\(^{797}\) and their method was used in manufacturing a single catapult bolt-head. However, this was a time-consuming process, and large-scale production was not feasible (Sim, a professional blacksmith, and Ridge had a manufacture time of 'three bolt heads...in an average time of 53 minutes',\(^ {798}\) whereas it took us over an hour to complete just one). It was decided, therefore, that, although it was costly, the bolt heads would be ordered from master smith Hector Cole, who uses the same method as Sim and Ridge.\(^ {799}\) Archaeological examples of bolt-heads from the period considered here have sockets with diameters ranging from 15mm to 28mm, which Bishop and Coulston believe to 'reflect the differing calibres of the machines that shot them'.\(^ {800}\) The sockets of the bolt-heads for this project have sockets measuring 20mm, in the middle of the archaeological range; given that the catapult in question, too, is in the middle range of possible sizes,\(^ {801}\) this seemed to be an appropriate size.

The shafts of the missiles were the simplest part to make. Philon provides us with a formula for calculating their length, with the missile nine times the diameter of the spring-hole.\(^ {802}\) *Clytaemnestra's* spring-hole is 7.5cm in diameter, making the missile 67.5cm long. It was possible to acquire hardwood dowelling 20mm thick off-the-shelf, and to cut it into appropriate lengths using the tenon saw. One end of each length of dowelling was then

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\(^{796}\)Bishop and Coulston (2009), 53-54.  
\(^{797}\)Sim and Ridge (2011), 84.  
\(^{798}\)Sim and Ridge (2011), 84.  
\(^{799}\)http://www.evado.co.uk/Hector%20Cole/index.html  
\(^{800}\)Bishop and Coulston (2009), 59.  
\(^{801}\)See Section 2 'Building *Clytaemnestra*' above.  
\(^{802}\)Philon, *Belopoeica* 54.27-55.1.
shaped so that it could be fixed into the socket of the bolt-head; this was done either using
the power-file or the band-sander, with the dowel being rotated. It is likely that this task
would have been done using a lathe in the ancient world, which would have achieved
similar results. As Philon tells us that there were no notches on the rear end of the bolt, none were added.

The bolt-heads were then glued to the shafts; how they were attached originally is unclear. Later arrows had their heads attached using tar, but there is no evidence for this
method of attachment in catapults bolts; riveting may have been a possible attachment
method, but again there is no evidence for this. The glue used (two part epoxy glue) was
completely inauthentic, but chosen because it has a firm enough hold on both the wooden
and metal components to make the missile as resilient as possible. This would not have
been a consideration for the ancients (in fact, the opposite would have been desirable, since
these were disposable weapons). However, given the limited resources available, the bolts
used in the testing phase needed to be reused, without constant repairs, and so it was
decided to make them as durable as possible. This turned out to be important, since the
main complication which slowed down the testing was missile breakages.

The flights (or fletchings) of the bolts were more difficult to attach to the shafts. Examples of catapult bolts from Dura show that wooden flights were used to stabilise the
missile as it flew. However, these date from the third century AD, and so cannot
necessarily be taken as representative of those used for bolts in the period considered.
Moreover, the bolts found at Dura were approximately half the length of those suitable for
this catapult, and so may not be comparable examples. Arrows are known to have used

803Philon, *Belopoeica* 77.5-6.
804Bishop and Coulston (2009), 206. See also Coulston (1985), 267 for evidence of arrowheads being glued
to their shafts. Comparative evidence also suggests the use of feathers for fletching arrows – see Coulston
(1985), 268.
805Bishop and Coulston (2009), 169-170. For the original references to these, see James (2004), 221-223,
catalogue numbers 806-808, 811, 818-820, 822, 832-833, illustrated in the same work on pages 223-226 and
229-230.
806Bishop and Coulston (2009), 169.
807Bishop and Coulston (2009), 169: the bolts found at Dura measured between 34cm and 37.5cm. These
are listed in James (2004), 221-223, catalogue numbers 805-842, and illustrated in the same work on
pages 223-230.
feathered fletchings, but again these date from a much later period (the example given by Bishop and Coulston also dates to the third century AD). There is some epigraphic evidence from 330BC which suggests that feathers might be used to fletch catapult bolts, though as the inscription mentions only unfeathered bolts it may be that some were deliberately left unfletched. From the evidence found at Dura, catapult bolts could have either two or three fletches.

An attempt was made to construct wooden flights for the bolts from ash, but there were several setbacks. The wood needed to be thin enough to be light in flight, but also strong enough to survive at least one shooting. Only a small amount of wood which met these criteria was available. In addition, because is was so thin, the fletchings were very difficult to cut out using the hand-saws; the wood vibrated during cutting and snapped if handled too roughly. There were also safety concerns if they were cut out using the bandsaw, since the fletches were too small and thin for a push-stick to be used to guide them. Moreover, the vibrations from the machine caused the wood to break apart. Three missiles were constructed with modern fletches, deliberately dyed a bright orange to ensure that the missile was highly visible, just as the shafts were later sprayed the same colour. Thin channels were chiselled out of the sides of the bolts to hold the fletches, which were then glued in place (again using the epoxy glue).

It was also decided to test some bolts unfletched, since there is no definite indication that bolts of this size had fletches fitted. These were made in exactly the same way, simply omitting the stage of attaching flights. Interestingly, these bolts behaved almost identically to those which were fletched under test conditions, though over a longer range they were very slightly more unstable.

808Bishop and Coulston (2009), 167. See also Coulston (1985), 267 on arrows from Dura with feathered fletches remaining intact. See also James (2004), 205 catalogue number 733, 206 Fig. 124, 207 Figs. 125-126, and 208 catalogue number 739.
809βέλη καταπαλτῶν...ἀπτέρωτα: IG II² 1627B, lines 337-8.
810James (2004), 221-223, catalogue numbers 805-842, and illustrated in the same work on pages 223-230.
811Fig. 66.
812Fig. 67.
Section 3 – Experimentation

Introduction and historical context

This section deals with the testing of the catapults' capabilities and compares them to the effects described by the ancient historical writers. However, before these comparisons can be made and before it is possible to design tests which can assess the ancient historians' descriptions, it is necessary to consider what the ancient writers say about the use of catapults. This chapter will deal with the main historical commentators who discussed or mentioned catapults in the period under consideration (350-100BC), along with the evidence which can be gleaned from the fragmentary historians (i.e. where references are traced from Brill's New Jacoby).813

The writers who have been chosen cover a wide range of literary genres, including works with a focus on history,814 biography,815 and technical writing.816 As a result, the types of evidence presented by these writers for the use of catapults and the level of detail which they provide vary significantly from author to author. In terms of the conventions and constraints placed on the authors, those within the biographical genre in particular are bound to focus in depth on their specific subjects rather than on some of the broader details (such as the use of catapults at battles in which their subjects participated). Moreover, individual authors, even in the genre of history, place particular emphasis in their works on certain aspects of their subject (for example, Polybius is particularly keen to emphasise the political facets of history, as well as the military).817 As a result, the types and level of

813BNJ was chosen as the main source for the section on the fragmentary historians mainly because it represents an updated and expanded version of Jacoby’s *Die Fragmente der Griechischen Historiker*; it also represents a more accessible source for tracing historians of this type. Since it has such a broad scope, it was decided that this would constitute the main source for this thesis of data from the fragmentary historians. It should be noted, however, that *BNJ* does not (at the time this thesis was submitted) provide a complete replacement for Jacoby's *FGH.*

814Polybius, Livy, Diodorus Siculus, Sallust, Curtius Rufus, Arrian, Timaios (see Champion (2014)), Timagemes (see McInerney and Roller (2014)), Silenos (see Williams (2014)), and Cincius Alimentus (see Habinek (2014)).

815Plutarch, Curtius Rufus, and Arrian.

816Moschion – see Roller (2014).

817Walbank (1979), 20. For how this affects the individual authors, see below.
details which the authors give us, their accuracy, and even their levels of interest in the use of artillery will vary from writer to writer. Additionally, the authors selected here date from the second century BC through to the second century AD,\(^{818}\) and this too may have an impact on the data which can be gleaned from their works. It is perhaps more likely that an author writing contemporaneously may be more accurate in his descriptions than one writing at a distance of five hundred years or more. Since catapult technology developed significantly within this time-frame, we may perhaps expect the later writers to make more unrealistic claims about the performances of the catapults in the time-frame considered by this thesis.

Rather than considering thematically the types of actions seen to be performed by the catapults, this chapter will consider the historical writers' works individually, since the level of detail which they give and the frequency with which they mention artillery and its use may go some way towards assessing their knowledge and understanding of the subject. The types of uses they discuss will be analysed thematically at the end of the chapter, along with suggestions of which tests may be used to determine their accuracy, followed by a comparison with Josephus to assess the extent to which literary tropes affect the writers as a whole. How the tests were performed can be seen in the following chapter, while comparisons to the historians' accounts based on those experiments will be made in the penultimate chapter of this thesis.

\(^{818}\)For the dates of the individual authors, see below.
Polybius

Polybius probably wrote his *Histories* in the mid-second century BC.\(^{819}\) As a result, Polybius wrote at least part of his history contemporaneously; unfortunately, the majority of this part of the *Histories* is no longer extant.\(^{820}\) The work itself is generally focussed on the history of the rise of Rome effectively from the 264 to 167BC.\(^{821}\) Polybius was also interested in critiquing other historical writers,\(^{822}\) however, as well as having a decided interest in political history.\(^{823}\) Nevertheless, his emphasis on the need for the historian to have experience of the things about which he writes,\(^{824}\) and Polybius' own personal military experience,\(^{825}\) suggest that what he tells us about the use of artillery in this period is likely to be based on reality.

Polybius mentions catapults directly only four times;\(^{826}\) elsewhere he refers more generally to 'engines',\(^{827}\) 'siegeworks',\(^{828}\) and 'missiles'.\(^{829}\) In some of these cases, while there are indications that catapults may have been used (references to missiles and missile range are unclear with regard to whether artillery or bows and slings were being used)\(^{830}\) the context of the narrative makes it impossible to distinguish which type of ranged weapon was used on these occasions. It may well be, however, that more references to artillery could have been contained in the missing books of Polybius' work, but such speculation cannot be of use here.

Although the references to catapult use are few and scattered, Polybius does give

\(^{819}\) Walbank (1979), 16.
\(^{820}\) McGing (2010), xiv-xv.
\(^{821}\) Though he also includes details of the Gauls' sack of Rome in 387/6BC – Polybius, 1.6. See McGing (2010), xvi-xxi.
\(^{822}\) Walbank (1979), 24.
\(^{823}\) McGing (2010), xxiv.
\(^{824}\) McGing (2010), xxii.
\(^{825}\) McGing (2010), x, and Walbank (1979), 13.
\(^{826}\) Polybius, 1.53.11, 1.74.4, 5.4.6, and 5.99.7.
\(^{827}\) μηχανή: Polybius, 1.38.8, 2.2.7, 5.3.6, and 5.4.6; μηχανήματα – Polybius, 1.48.2, 1.48.4-5, and 5.71.5
\(^{828}\) ἐργα: Polybius, 1.38.8, 1.42.8-9, 1.48.3, 1.48.8, 3.18.4, 4.63.2, 5.3.6, and 5.100.1
\(^{829}\) βόλος: Polybius, 1.74.4, 4.70.2, 4.71.10, 5.13.10, and 5.100.2 (but this last is specifically connected to the use of catapults – see Polybius 5.99ff)
\(^{830}\) See below.
his reader a sense of how they were used. In the two most detailed incidents, Polybius is clear that the catapults were used purely as anti-personnel weapons. They are used to harass and annoy defending forces, but not directly against city walls. At the siege of Pale, the first of these two descriptions, catapults were used to provide covering shots for sappers who were undermining the city wall. In the second, the siege of Thebes Phthiotides, it is clear that the injury and disabling of the defenders was the object as much as their deaths. Beyond this, Polybius gives us very little information, omitting even the range at which the catapults were operating. We are not told the size of catapults used, and although Polybius tells us that stone-shooting catapults were used at Pale, the term he uses for 'missile', βέλος, could refer as easily to bolts as to stones; the context of the passage does not provide any further clarity.

Other information can be gathered from references to sieges where catapults are not directly mentioned. At Stratus, for example, Polybius tells us that an attacking army deliberately formed up outside the city walls beyond the range of the defenders' missiles before challenging the defenders to come out. While it is impossible to tell whether the range was that appropriate to a catapult or to a hand bow, or indeed what type of missiles the defenders had, there is the implication that attacking forces were well aware of the maximum reach of missiles coming from a city wall, and could therefore avoid stationing themselves in that area. Again, Polybius does not tell us the range.

Polybius' time as hipparch in 170/169BC, as well as his opinion 'that one of the vital qualifications for writing history was practical...military experience', should mean that he had knowledge of the use of artillery on the battlefield and it could be expected that at the very least he had seen a catapult in action. Why, then, does artillery get so little

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831Polybius, 5.4 and 5.99-100.
832Polybius 5.4.
833Polybius, 5.100.
834Polybius, 5.13.10: 'he halted [his army] outside the range of a missile' (ἐπέστησεν δύναμιν ἐκτὸς βέλους).
836McGing (2010), ix.
mention and description in Polybius' work? It could be that catapults were so commonplace that Polybius felt no need to mention them in most descriptions of battles and sieges, expecting his readers to assume their presence. He may not have been particularly interested in catapults, or they may have seemed less important to him and to his narrative than the actions of the infantry, cavalry, and generals. On the other hand, it may simply have been that artillery was used only occasionally, which is a distinct possibility given that it would either have had to be transported in a siege train or built from scratch on site, making catapult use time consuming and resource hungry.

Livy

Livy was writing in the late first century BC. Like Polybius, his work was a historical survey of the history of Rome, beginning much earlier than Polybius with the mythological founding of the city. Being slightly later than the period with which this thesis is concerned, Livy's descriptions of catapults may well be influenced by the more developed models of this period and any changes in the ways in which catapults were used since the addition of curved arms to the bolt-shooting catapult. Briscoe has noted that Livy's 'battle scenes are often stereotyped', which means that care must be taken when considering his references to and descriptions of artillery in action.

Livy refers directly to catapults at sixteen incidents in this period. It is clear from the accounts given by Livy that, like Polybius, he saw the catapult mostly as an anti-personnel weapon. Of these sixteen occasions, six show them being used in this way.
while the other references to catapults do not make clear how (or, on occasion, whether) they were used. Catapults are seen by Livy to be used in much the same way as their predecessors, the bow and the sling.\footnote{Livy, 24.34.8.}

The impact on morale of this type of targeting is also inferred by Livy, in an incident where Scipio was attempting to capture Locri: a catapult bolt struck the man beside him, and this scared the general (described as \textit{territus}) into moving his camp out of catapult range.\footnote{Livy, 29.7.6-7. For a quotation and translation of this passage, see above.} The phrasing of this passage (in particular the phrase 'having advanced to the walls' \textit{progressus ad murum}) suggests that the range was fairly short, though this is unclear.\footnote{Livy, 29.7.6-7. For a quotation and translation of this passage, see above.} Livy may want his reader to think that the bolt was aimed directly at Scipio; alternatively, he may want us to think that it was chance that the bolt struck so close to the Roman leader. However, his comments on the incident are limited to what happened from Scipio's viewpoint, and he does not elaborate on what he wants his readers to believe. In addition to this incident, where catapults (even stone-shooting ones) were used at a siege it was the other engines and sapping which made walls fall, not the artillery,\footnote{Livy, 31.46.15.} which strengthens the view that catapults were used mainly for anti-personnel purposes.

Interestingly, Livy notes that it was possible for an attacking force to come inside the range of a defending force's catapults and thus be safe from their missiles;\footnote{Livy, 26.6.4: 'the armed men were not so much standing up to the Romans who were breaking in, as the gate, furnished with \textit{ballistae} and \textit{scorpiones}, was keeping the enemy far away' (\textit{neque tam armati inrumpentibus Romanis resistebant, quam porta ballistis scorpionibusque instructa missilibus procul hostis arcebat.}); see also Livy, 26.43.3-26.45.4, 29.7.6-7, and 32.5.13.} different weights of missiles would be used at different ranges to counteract this problem.\footnote{Livy, 24.34.10.} Livy also comments on forces being able to estimate missile range.\footnote{Livy, 29.7.6-7 (see above). See also the experiment table below for further details.} Moreover, he describes the

\begin{enumerate}
\item \textit{cubitalibus fere causis aperuit, perquae cavae pars sagittis, pars scorpionibus modicis ex occulto petebant hostem.} Livy, 26.6.4: 'the armed men were not so much standing up to the Romans who were breaking in, as the gate, furnished with \textit{ballistae} and \textit{scorpiones}, was keeping the enemy far away' (\textit{neque tam armati inrumpentibus Romanis resistebant, quam porta ballistis scorpionibusque instructa missilibus procul hostis arcebat.}); see also Livy, 26.43.3-26.45.4, 29.7.6-7, and 32.5.13.
\item \textit{progressus ad murum, scorpione icto qui proximus eum forte steterat, territus inde tam periculoso casu receptui canere cum iussisset, castra procul ab ictu teli communit.} See also Livy, 38.27 on how missile weapons could affect the morale of an enemy.
\end{enumerate}
logistics of transporting catapults: wagons might be used to carry them.  
This is an important aspect of the use of artillery, because how easily catapults could be moved affects their positioning in the field and the practicality of moving them in a siege train.

Livy's surviving work is substantially longer than Polybius', which may in part explain the larger number of references to artillery in his work. However, given how much more of Livy's work survives, it is only the level of detail which he provides which really separates him from Polybius. He considers factors which Polybius does not mention, including the logistical aspects to catapult use. Moreover, Livy, like Philon, notes that catapult building is an expensive undertaking, a practicality which Polybius does not mention. Taken together, these factors suggest a stronger interest in the subject than Polybius had, and would mean that Livy's writing could be anticipated to be more accurate than Polybius' when it comes to the experimentation stage of this thesis, were it not for the fact that their accounts are remarkably similar with regard to the actual use of artillery in the field.

**Diodorus Siculus**

Diodorus probably wrote in the mid-first century BC, and like Livy wrote from a mythological period through to almost his own time. While Diodorus discusses history from the rest of the Mediterranean, including Italy, Egypt, and Asia Minor, his primary interest is in the history of his home, Sicily, and the rest of Greece. The surviving parts of his work mainly cover the period from 480BC to 302BC, along with fragments. As with

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848Livy, 42.53.4.
849Livy, 36.22.10-11
850Livy, 34.34.3 and Philon, *Belopoeica* 57.25-27 and 62.16-17.
Livy, we must be wary that Diodorus' later date may mean that any references to catapults may be made with reference to the more advanced designs of this period. We must also be wary of Diodorus because of the way in which he compiled his material. He has a poor reputation among modern scholars for confusing his evidence and making mistakes, and it is impossible to tell what Diodorus has taken verbatim from his sources and 'what he has consciously interpolated'.

Of all the authors in this chapter, Diodorus refers to catapults the most, mentioning them directly on thirty one occasions. Like Livy and Polybius, Diodorus describes the catapult as used mainly as an anti-personnel weapon and for covering shots, with fifteen of the references to catapults showing them being used in this way. He also implies that catapults were being used to injure and disable as much as to kill. Unlike the other two authors, however, Diodorus gives us examples of catapults being used directly against the walls of fortifications, and successfully effecting a breach on up to three occasions (at Rhodes and Croton). He also mentions the use of catapults on ships, and adds some information about their use in battle formation: the ships armed with artillery (warships) would be located at the front of a fleet with transport and cargo ships behind them and that catapults were set on platforms on the ships.

Diodorus seems uninterested in how catapults were transported; where he mentions catapults being moved in a siege train, the only information that he gives is their

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855Diodorus Siculus, 16.74.4; 16.75.3; 17.24.6; 17.26.6; 17.41.3; 17.42.1 and 17.42.7; 17.45.2; 17.85.7; 18.51.1; 18.20.2; 18.70.2 and 18.70.7; 18.71.3; 20.45.5 and 20.45.7; 20.48.1, 20.48.3 and 20.49.4; 20.51.2; 20.54.4; 20.75.3-4; 20.83.1; 20.85.1, 20.85.3, and 20.85.4; 20.86.2; 20.87.1 and 20.87.4; 20.88.2; 20.91.6; 20.95.2; 20.96.3 and 20.96.6; 20.109.1; 21.4.1; 21.8.1; 22.10.7; 24.1.1; and 24.1.2.
857Diodorus Siculus, 17.42.7, 17.45.2, 20.86.2, 20.87.1, 20.88.2, 20.95.4 (where the stone-shooting catapults were used in conjunction with rams), and 21.4.1.
858Diodorus Siculus, 20.87.1 and 20.95.5 (both at Rhodes, though it is not clear for the second reference whether rams or catapults, or both, created the breach), and 21.4.1 (at Croton).
859Diodorus Siculus, 17.42.1, 20.49.4, 20.51.2, 20.83.1, 20.85.1, and 20.86.2.
860Diodorus Siculus, 20.83.1.
861Diodorus Siculus, 20.85.4.
presence, giving less detail than Livy. Nevertheless, Diodorus notes that siege trains could be transported by sea. Like Livy, however, Diodorus hints at catapults being constructed on site. He also describes attacking forces coming within the minimum range of the defenders' missiles, and his account is similar to Livy's. He is also concerned with the effects which catapults could have on the morale of defending forces, commenting on how an array of siege weaponry held by an attacker could be ‘astonishing’ to the defenders, as could unabating attack from artillery. Like the authors already discussed, Diodorus considers the placement of artillery and how it might affect the outcome of a conflict. He also shows us that commanders recognised the need to position camps outside of missile range and had an awareness of that range's extent. He notes that range could be influenced by the type of catapult, that bolt-shooting catapults had a greater range than stone-shooters, and that catapults of smaller calibre had the greatest overall range.

Diodorus’ interest in artillery seems to be significantly greater than that of the authors already considered in this chapter. Diodorus is prepared to give specific details about the catapults used in conflicts, unlike Livy and Polybius, who remain vague; he also gives us a figure of two hundred men operating catapults within a helopolis at Salamis

(though he refrains from telling us the exact number of catapults in the tower).

863E.g. Diodorus Siculus 18.51.1: '[he had] all kinds of missiles and both bolt-shooting and stone-shooting catapults and every other supply appropriate for besieging a city' (...βέλη δὲ παντοδαπὰ καὶ καταπέλτας ὀξυβελεῖς τε καὶ πετροβόλους καὶ τὴν ἄλλην χορηγίαν πᾶσαν τὴν ἀνήκουσαν πρὸς πολιορκίαν).
864Diodorus Siculus, 20.45.1.
865Diodorus Siculus, 18.70.2: ‘others were concerned with making weapons and the preparation of bolt-shooting catapults' (...)ἄλλοι δὲ περὶ τὰς ὁπλοποιίας καὶ τὴν κατασκευὴν τῶν ὀξυβελῶν καταπελτῶν ἐγίνοντο). See also Diodorus Siculus, 24.1.1-2.
866Diodorus Siculus, 20.16.6-7, though it is not clear here whether the missiles are being discharged by catapults.
867καταπληκτικός: Diodorus Siculus, 20.48.1 and 20.88.3; συνεχής: Diodorus Siculus, 20.88.3.
868Diodorus Siculus, 20.45.6.
869Diodorus Siculus, 20.83.3: ‘...when the force had disembarked he encamped near the city, making the camp outside of missile range' (...ἀποβιβάσας δὲ τὴν δύναμιν κατεστρατοπέδευσεν πλησίον τῆς πόλεως, ἐκτός βέλους ποιημένου τὴν παρεμβολήν). See also Diodorus Siculus, 20.86.3 where Demetrius Poliorcetes removes his siege weaponry out of the defenders' range at Rhodes.
870Diodorus Siculus, 20.85.2.
871Diodorus Siculus, 20.85.3.
872E.g., at Salamis, he refers to the presence of a three-talent stone-shooting catapult (Diodorus Siculus, 20.48.3) and three-span bolt-shooting catapults (Diodorus Siculus, 20.49.4). Three-span bolt-shooters are also described as being used on ships by Demetrius Poliorcetes (Diodorus Siculus, 20.83.1). Three-palm (i.e. one-span) bolt-shooters are mentioned at Rhodes (Diodorus Siculus, 20.85.3).
also claims that, at the siege of Rhodes, over fifteen thousand, eight hundred missiles were shot by the defenders in one night.\textsuperscript{874}

This level of detail raises two possibilities. Either Diodorus possessed more information than the other historians, or he may have given this kind of specific detail to persuade his reader of his authority on the subject (or to add colour to his narrative) without knowing for certain that these 'facts' were correct. Large round numbers are always to be treated with caution, particularly where even Diodorus notes that they are exceptional.\textsuperscript{875} Moreover, the idea that he may have been adding colour to his account may be supported by his narration of the methods by which Agathocles tormented the people of Segesta in 307BC: one of the methods used was to shoot humans out of catapults,\textsuperscript{876} something which is not attested elsewhere and which, given the scale of the catapults needed for such a feat, would require catapults of immense size simply to allow the victims to pass through the aperture. This makes Diodorus' account of the torture appear fantastical, or at the very least exaggerated, and also raises questions about his understanding of catapult technology.

\textbf{Sallust}

Sallust was also writing in the mid-first century BC.\textsuperscript{877} The work considered here, the \textit{Jugurthine War}, was chosen because it fits into the time-frame selected for this thesis;\textsuperscript{878} his other works concern the first century BC and were therefore excluded. The \textit{Jugurthine War} is a much shorter history than those already considered and focusses on the period 112-105BC.\textsuperscript{879} However, his writing has a strongly moral focus, which throws off

\begin{itemize}
  \item \textsuperscript{874}Diodorus Siculus, 20.96.2.
  \item \textsuperscript{875}Diodorus Siculus, 20.96.2. It should be noted, however, that Diodorus qualifies the figures he gives just under a quarter of the time – see Rubincam (2003), 461. Moreover, this is far from an outlier in the range of numbers he gives throughout his work. See Rubincam (2003), 454-455.
  \item \textsuperscript{876}Diodorus Siculus, 20.71.2.
  \item \textsuperscript{877}Pelling (2005).
  \item \textsuperscript{878}Pelling (2005).
  \item \textsuperscript{879}Handford (1963), 30.
\end{itemize}
balance (to some extent) his military coverage,\textsuperscript{880} and this perhaps is why his references to artillery are so limited.\textsuperscript{881} Sallust had some military experience and 'as praetor in 46 he took part in the African campaign.'\textsuperscript{882} This means that we must treat his few references to catapults with caution, since it is likely any knowledge he had of them would be coloured by the innovations in their design which occurred in the late second century BC.

Sallust mentions catapults only twice in his history of the \textit{Jugurthine War}.'\textsuperscript{883} On both occasions, the word used for 'catapult' is \textit{tormentum}, which tells us only that the artillery used was torsion-powered and not the type of missile used. The only other detail which Sallust provides is that on the second occasion, the catapults were used as anti-personnel weapons by a defending force, against soldiers who were not attacking the walls of a fort directly, while other attacking forces were scaling the walls.'\textsuperscript{884} On the whole, then, Sallust's work is not of much use to this study except to confirm the evidence from other sources that catapults were used mainly as anti-personnel weaponry.

\textbf{Plutarch}

Unlike the works considered up to this point, those of Plutarch's writings which are discussed here are biographical in nature. They make up part of his \textit{Parallel Lives}, which have strongly didactic and moral intentions,'\textsuperscript{885} as such, his discussion of the military aspects of his subjects' lives is very limited and mainly concerns those incidents which show off the characters of the men in his biographies. This significantly limits his usefulness for the purposes of this thesis. Given also his late date (he was probably writing in the late first to early second century AD),'\textsuperscript{886} both his distance in time from his subjects

\textsuperscript{880}Pelling (2005).
\textsuperscript{881}See below.
\textsuperscript{882}Pelling (2005).
\textsuperscript{883}Sallust, \textit{Jugurthine War} 57 and 94.
\textsuperscript{884}Sallust, \textit{Jugurthine War} 94.
\textsuperscript{885}Plutarch, \textit{Life of Alexander} 1. See also Russell (2005).
\textsuperscript{886}Russell (2005).
and the extensive developments which took place in the field of artillery may make his accounts of the use of artillery less accurate (and potentially more exaggerated) than we might hope.

Plutarch shows a decided lack of interest in the use of artillery. For example, he does not mention the presence of artillery at Perinthus or the fact that the catapults were loaned to the Perinthians by Byzantium in 340BC, which is emphasised in Diodorus' account.\(^{887}\) The majority of his biographies of men from this period contain no references to artillery, despite mentioning battles, sieges, and campaigns.\(^{888}\) He does at least acknowledge his agenda in his introduction to the *Life of Alexander*, explaining that his focus and interest lie in the characters of the men whose biographies he wrote rather than (necessarily) their actions or the details surrounding incidents in their lives, including the types of warfare in which they were involved.\(^{889}\) Indeed, the one part of his works which considers catapult design and engineering in any detail does so only because of Plutarch's interest in Archimedes.\(^{890}\) The *Life of Sulla* only hints at the presence of catapults at the siege of Athens (the term 'machine' is used, but artillery is not specifically mentioned),\(^{891}\) and the use of fire-missiles by the defenders at the same siege (which might or might not refer to catapult missiles).\(^{892}\)

Unusually for Plutarch, his *Life of Alexander* tells us that catapults were present at Gaza\(^{893}\) and indicates that missiles (possibly from catapults, although this is unclear) were used as anti-personnel weapons.\(^{894}\) He also notes that an arrow shot from a bow could pierce armour and lodge there, though he does not tell us the range from which the missile was shot.\(^{895}\) In his *Life of Demetrius* he gives us at least some details of the capabilities of

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\(^{887}\)Plutarch, *Phocion* 14. See also Diodorus Siculus, 16.74.4

\(^{888}\)Timoleon, Demosthenes, Phocion, Pyrrhus, Eumenes, Agis, Cleomenes, Aratus, Fabius Maximus, Philopoemen Flamininus, Aemilius Paulus, Cato the Elder, Tiberius Gracchus, Gaius Gracchus, and Gaius Marius.

\(^{889}\)Plutarch, *Alexander* 1.

\(^{890}\)Plutarch, *Marcellus* 15-17.

\(^{891}\)μηχανή: Plutarch, *Sulla* 12.1 and 12.2.

\(^{892}\)πυρπολεῖσθαι βαλλόμενα: Plutarch, *Sulla* 12.3.

\(^{893}\)Plutarch, *Alexander* 25.3.

\(^{894}\)Plutarch, *Alexander* 63.2.

\(^{895}\)Plutarch, *Alexander* 63.3.
catapults in this period: Demetrius is shot and wounded by catapult bolts twice, once through the jaw and mouth, and once through the neck.\(^{896}\) Again, the range is left unmentioned. Plutarch does give a range at one point in this work, however: he describes the testing of a piece of armour which is shot at 'twenty paces', and he reports that the missile only scratched it, though this may be to emphasise the strength of the armour.\(^{897}\) In the *Life of Marcellus*, which gives us the most detailed description of catapults of any of his works, Plutarch reports that Archimedes compensated for the fact that large catapults had a minimum effective range by designing lighter catapults.\(^{898}\) Plutarch also comments on the effects catapults had on the morale of the opposing forces: according to Plutarch, the Romans fighting at Syracuse were so petrified (περίφοβος) by Archimedes' engines that they ran away if they even thought one of his machines was being trained on them.\(^{899}\) A further detail given by Plutarch in this work is that catapults might be mounted on ships.\(^{900}\)

**Curtius Rufus**

Curtius Rufus was probably writing in the mid-first century AD, though his date is decidedly problematic.\(^{901}\) Again, this means that significant developments in catapult technology happened between the period discussed in the *History of Alexander* and the time at which it was written. Curtius Rufus' work is 'semi-biographical',\(^{902}\) which means that when thinking about his work all of the caveats applied to Plutarch (above) must also be considered. This is especially true with regard to Curtius Rufus' tendencies towards moralising.\(^{903}\) In addition, Curtius Rufus' technical knowledge, and in particular his

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\(^{896}\)Plutarch, *Demetrius* 33.2 and 40.3 respectively.  
\(^{897}\)Plutarch, *Demetrius* 21.3: 'the maker, Zoilos, ordered a catapult bolt to be discharged at it [the armour] from twenty paces; the iron remained intact where it struck, but it only just bore a faint scratch, just like one from a graver.' (ὁ τεχνίτης Ζωῗλος ἐκέλευσεν ἐξ εἴκοσι βημάτων ἀφεῖναι καταπελτικὸν βέλος, οὗ προσπαθοῦντος ἄφοβος διέμεινεν ὃ, ἀμυχὴν δὲ μόλις ἔσχεν ἀμβλεῖαν, οἷον ἀπό γραφείου).  
\(^{898}\)Plutarch, *Marcellus* 15.5.  
\(^{899}\)Plutarch, *Marcellus* 14.3.  
\(^{900}\)Heckel (2004), 1-3.  
\(^{901}\)Heckel (2004), 9.  
\(^{902}\)Heckel (2004), 11-12.
'military narrative' has been considered 'poor', despite his military experience. His references to artillery must therefore be considered carefully.

Curtius Rufus provides us with very little detail about the use of catapults. His account of the siege of Tyre does provide some insight into how catapults were deployed, though. He tells us that the defensive catapults were initially raised considerably higher than the attackers' engines, on the city walls, while Alexander's forces had to rely on catapults set up on ships, which they found problematic. He tells us that siege towers were later deployed by the attacking forces, though without specifying whether catapults were employed within them, as a way of combating the defenders' height advantage. He corroborates Polybius' and Livy's evidence that generals were aware of the maximum range of the defenders' catapult missiles, noting that Alexander positioned his static towers out of the Tyrians' missile range. At the same siege, he also presents us with a rare example of catapults being used directly against the city walls, rather than simply as anti-personnel weapons.

Curtius Rufus mentions the use of catapults in the field on two further occasions. In the first, Alexander's forces attempted to break down a barricade which had been erected in Nautaca. These catapults were used together with siege towers, which suggests that they needed to be elevated in order to strike the defending forces. The language used by Curtius Rufus suggests that the catapults were bolt-shooting: he uses the term tormentum for the catapults, which could indicate any type of torsion catapult, but the word he uses for missile, telum, indicates something sharp-pointed. This suggests that the catapults were being used for anti-personnel purposes rather than to demolish the barricade, though this is

904Heckel (2004), 14.
905Curtius Rufus, 4.2.12.
906Curtius Rufus, 4.2.9. See also 4.3.13.
907Curtius Rufus, 4.3.8 and 4.4.20.
908Curtius Rufus, 4.3.8: 'He also added to the breadth of the causeway, so that the towers which had been erected in the middle [of the causeway] might be far out of missile range' (latitudinem quoque aggeri adiecit, ut turres in medio excitatae procul teli iactu abessent).
909Curtius Rufus, 4.3.13.
910Curtius Rufus, 8.2.26.
not explicit. Similarly, at Mazagae, Curtius Rufus does not specify the type of catapult, using the generic term for 'engine' or 'machine' (*machina*), but again uses the word *telum* to describe the missiles used.⁹¹¹ He later describes the missiles as 'very heavy spears'.⁹¹² In both cases, Curtius Rufus notes that Alexander's catapults and other machinery had an effect on the morale of peoples who had not encountered this type of technology before. At the barricade, the missiles from the catapults put the enemy to flight,⁹¹³ while at Mazagae, not only did the siege equipment force the defenders to surrender,⁹¹⁴ but Curtius Rufus also comments that the defenders 'said that the *pila* and towers and heavy spears sent out from the catapults were not suited to mortals'.⁹¹⁵

**Arrian**

Arrian was probably writing in the mid-second century AD.⁹¹⁶ He had a great deal of military experience,⁹¹⁷ and wrote several military manuals, two of which are considered here.⁹¹⁸ This military experience may be problematic for this thesis: it is very likely that Arrian, who 'commanded two Roman legions'⁹¹⁹ would have seen the more developed catapults of his own period in action, and this may have affected his descriptions of catapults from the earlier period considered here.⁹²⁰ However, his use of Ptolemy as his main military source for his *Anabasis* may limit the effects of his own experience on his writing,⁹²¹ though it is impossible to say by how much or if does at all. The fact that Arrian takes Xenophon's *Anabasis* as his 'model' for his work of the same name, while influencing

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⁹¹¹Curtius Rufus, 8.10.31
⁹¹²Curtius Rufus, 8.10.32: *praegravis hasta*.
⁹¹³Curtius Rufus, 8.2.26. The verb used is *concedere*.
⁹¹⁴Curtius Rufus, 8.10.33.
⁹¹⁵Curtius Rufus, 8.10.32: *pila quoque muralia et excussas tormentis praegraves hastas negabant convenire mortalibus*.
⁹¹⁷Hamilton (1971), 15 and 18.
⁹¹⁸Hamilton (1971), 16.
⁹¹⁹Hamilton (1971), 15.
⁹²⁰Conversely, this may make his *Tactica* and *Ectaxis* (discussed below) more useful to us because it is likely to be based on his personal experience.
⁹²¹Hamilton (1971), 21
the work in other ways, is unlikely to have had a direct impact on his descriptions of artillery, since catapults do not feature at all in Xenophon's works, though it does limit the scope of Arrian's *Anabasis* as a whole. This work is semi-biographical, like Curtius Rufus', though less moralising and with more interest and accuracy in military matters. We must, therefore, again apply the caveats which were considered above in the case of Plutarch's works.

One difficulty in using Arrian as a source for the use of catapults and artillery in the ancient world is that he applies the word 'machine' or 'engine' (μηχανή) indiscriminately to all forms of siege engine, making it unclear what type of technology he means throughout his history of Alexander (the *Anabasis*). Therefore, this overview is limited only to examples where it is absolutely clear that Arrian refers to catapults specifically, rather than to any other form of siege equipment. These examples can be distinguished from the more general applications of the word μηχανή by context, i.e. where it is used together with words for 'missile' (e.g. βέλος) or verbs for throwing or shooting (e.g. βάλλω). Arrian only specifically mentions stone-shooting catapults once, at Halicarnassus, and in the *Anabasis* he uses a specific word for catapult only once.

The majority of incidents described by Arrian where catapults can be identified confidently show artillery in a siege context. According to Arrian, on three of the nine occasions on which he records the use of artillery in sieges, catapults were used together with siege towers, which he suggests were needed in order to begin the bombardment of

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924Hamilton (1971), 27-33.
925E.g. Arrian, *Anabasis* 2.20.1-3: there are several references to 'machines' (μηχανή) throughout this section of his work. The fact that they are situated on ships indicates that they are likely to be catapults, but there is not sufficient data in the rest of the passage to confirm that they are not (for example) rams or scaling ladders. Since he consistently uses the word πύργος for siege tower (along with other types of tower), we can be fairly confident that the 'machines' here are not siege towers.
926Arrian, *Anabasis* 1.22.2.
927καταπέλτης: Arrian, *Anabasis* 2.27.2.
928Arrian, *Anabasis* 1.20.8, 1.22.2, 2.18.6, 2.23.3, 2.26.4-27.2, 4.2.3, 4.26.5, 4.27.2, and 4.30.1.
929Arrian, *Anabasis* 1.22.2, 2.18.6, and 4.26.5.
a city. At Tyre, Arrian hints at the use of catapults from ships, which corroborates the accounts of Diodorus and Curtius Rufus. He also describes catapults being used as anti-personnel weapons at Gaza (the second city of that name which Alexander encounters). Arrian's account of the siege of Gaza confirms that it was possible for an experienced general to judge catapult range, though Alexander was hit by a catapult bolt after entering the defenders' range at Gaza somewhat recklessly. Arrian also describes catapults being used to provide covering shots at river crossings, and on one occasion to defend a pass.

Additionally, Arrian comments on the effect of artillery on the morale of those who had not encountered catapults before. The Scythians, according to him, were unable to judge their range and were forced back from the river edge they were defending. We are also told about the penetration catapult bolts could achieve on two occasions: first, Arrian gives us an account of a catapult bolt striking Alexander through his shield, body armour, and into his body; second, a Scythian is hit through his shield and armour, and killed. Arrian does not describe the range was at which either of these strikes occurred, nor exactly what type of armour was used by Alexander or the Scythian. In another incident, an Indian king is killed by a catapult bolt, but in this case Arrian does not specify what, if any, armour he was wearing or the range from which he was shot.

In another of his works, the Tactica, Arrian mentions catapults only once, and without much detail. The only information which can be gained from this passage is that

930 Arrian, Anabasis 1.20.8.
931 Arrian, Anabasis 2.23.3.
932 Arrian, Anabasis 4.2.3.
933 Arrian, Anabasis 2.26.4-27.1.
934 Arrian, Anabasis 2.27.2. NB, this is the first Gaza encountered by Alexander.
935 Arrian, Anabasis 1.6.8 and 4.4.4.
936 Arrian, Anabasis 3.18.3.
937 Arrian, Anabasis, 4.4.4.
938 Arrian, Anabasis 2.27.2.
939 Arrian, Anabasis 4.4.4.
940 In the both cases, the word 'thorax' (θόραξ) is used, which could refer to scale, plate, or linen armour. See LSJ under θόραξ.
941 Arrian, Anabasis 4.27.2.
942 Arrian, Tactica 43.1. Again the word μηχανή is used and the identification of a reference to artillery here is contextual.
catapult stones could struggle to destroy a target set up for them. Arrian's *Ectaxis* is also worth consideration, since although it dates from a considerably later period, discussing the Roman army of the second century AD, it is the only account we have of the position of artillery in the marching and battle order. According to Arrian, the catapults were positioned just after the cavalry on the march, but in front of the legionary standards, officers, and javelinmen, and ahead of the auxiliaries. Interestingly, in battle the artillery was to be positioned on the flanks, not in the centre, and behind the main battleline. This indicates that catapults had a significant range, but that they either needed protection (so they were positioned behind the main body of troops) or that, if positioned in front of the army, they would obstruct the infantry and cavalry, or both. The catapults were only supposed to shoot once the enemy was in range, and Arrian seems to indicate that their range was not significantly different to that of hand bows and javelins (or that the catapults' range could be adjusted to match theirs), since his phrasing implies that they would be loosed at the same time. The aim of this, according to Arrian, was as much to panic the enemy as to cause physical damage. It is worth noting, however, that by this point catapult technology had developed significantly: curved arms had been added to bolt-shooting catapults, stone-shooting catapults had significantly different frames, the proportions of the spring-frames had been further adjusted, and the *cheiroballistra* had been developed. All of these developments are likely to have led to improved range, and the *cheiroballistra* would have been significantly more portable than its predecessors. Therefore, the usefulness of this passage is limited by the passage of time between its own period and that considered by this thesis. However, the effects on morale and catapults' use alongside unmechanised missile weapons can be paralleled in the other works considered

943Hamilton (1971), 16.
944Arrian, *Ectaxis* 4-6. The word καταπέλτης is used here rather than μηχανή.
945Arrian, *Ectaxis* 7-8
946Arrian, *Ectaxis* 19. Here, Arrian uses the word μηχανή to refer to the artillery.
947Arrian, *Ectaxis* 25. Again μηχανή is used for the catapults.
949Marsden (1969), 43.
here.

**The Fragmentary Historians**

The information which can be gained from the fragmentary historians must be considered in order to take a full account of the evidence available, albeit that there are some overlaps with the accounts given by the authors discussed above (since they drew on the fragmentary historians in their own narratives), and despite the fact that what further details they give us can be limited both in scope and number. The information which can be found within the corpus of the fragmentary historians is both scattered and vague, though some of the details which can be gleaned contain evidence which can be tested at the experimental stage of this thesis or corroborate the other historians who have been considered here.

Moschion,\(^950\) who seems to give the most specific details, was used as a source by Athenaeus, who comments on the siege weaponry developed by Archimedes and suggests that his machines could throw missiles three talents in weight (approximately 80kg) or five *peches* long (approximately 5m) a distance of one *stadion* (approximately 190m).\(^951\) Such missiles would be considerably larger than those suitable for the catapults constructed for this thesis, with the catapults approximately seven times larger than the replica bolt-shooter and five times the size of the stone-shooting catapult. In comparison to the largest washers found in the archaeological record, Moschion's bolt-shooter's washers would be three and a half times larger; those for the stone-shooter would be three times the size.\(^952\) Given that Moschion's catapults are significantly larger than those indicated by the archaeological record, Moschion's account appears somewhat implausible. This does not entirely rule out

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\(^950\)Writing a technical treatise of unknown title, possibly on mechanics, contemporaneously with the events he describes c. 240BC – see Roller (2014).

\(^951\)Moschion, *BNJ 575 F1* = Athenaeus, *Deipnosophistae* 208C. The words used for stone-shooting catapult here is λιθόβολος; no word is given for bolt-shooter. The implication seems to be that the same catapult could be used to shoot stones or bolts.

\(^952\)See Rihll (2007), 296.
his evidence, since there are countless reasons which could explain why larger washers
have not survived (including the possibility that they could have been melted down and
reused). Certainly, Philon suggests that stone-shooting catapults could be that size.\footnote{Philon, \emph{Belopoeica} 51.26.} This
range gives us a possible benchmark for performance, though it would appear improbably
long. Additionally, like Diodorus, Athenaeus and his source Moschion mention the use of
catapults on ships, giving their calibres as those listed above.\footnote{Moschion, \emph{BNJ} 575 F1 = Athenaeus, \emph{Deipnosophistae} 208C.} Timaios\footnote{Timaios, \emph{BNJ} 566 F164 = Diodorus Siculus, 5.18.3} is used as a
source by Diodorus Siculus, where the Baliare's skill with the sling is compared to how
catapults were used: he suggests that slings could exert as much force as a catapult, and
were used as anti-personnel weapons in much the same way.\footnote{Tnearchos, \emph{BNJ} 133 F1 III = Arrian, \emph{Indica} 24.6-7. The word used of the emotional effect on the enemy
who were being shot at with catapults (ἐκπλαγέντες) indicates either that they were 'astonished' or
'amazed'.} Nearchos is used as a
source by Arrian, where he comments on the impact the use of catapults had on the morale
of those who had not experienced artillery before.\footnote{Writing histories in the mid- to late first century BC, surviving fragments of which 'concern Ptolemy I (F
3), Antiochos IV (F 4), the Hasmoneans (F 4-6), and Ptolemy XII (F 9)' – McInerney and Roller (2014).}

Other references to catapults in the fragmentary historians are much less useful, but
provide vivid descriptions of artillery. Timagenes of Alexandria,\footnote{Timagenes of Alexandria, \emph{BNJ} 88 F 15 = Ammianus Marcellinus, 15.12.1 (...ut catapultas tortilibus
nervis excussas).} for example, used as a
source by Ammianus Marcellinus, describes the way in which Gaulish women threw out
kicks and punches while fighting as similar to the way in which catapults shot missiles.\footnote{Who wrote a history of 'Hannibal and of the Second Punic War', 'accompanied...[Hannibal] on his
campaigns', and probably wrote in the late third and early second century BC – Williams (2014).} These references may also tell us that a particular type of catapult was present in one place
or another at any given time, without providing any further detail: Silenos\footnote{Silenos, \emph{BNJ} 175 F6 = Livy, 26.49.3. See also above, under Livy.} is directly
referred by Livy when he estimates the number of bolt-shooting catapults captured by
Scipio after the fall of New Carthage.\footnote{Who probably 'wrote one work, in Greek, covering Roman history from the beginning until his own day'...}
source, Livy mentions the presence of artillery at the siege of Locri. Overall, then, the fragmentary historians are of little use to this study, though there are occasions on which they can be used to support comments made by the authors whose work is more extant.

**Summary**

There are several commonalities in the accounts of the ancient historians. The use of catapults for anti-personnel purposes, particularly to remove defenders from battlements or to provide covering shots, stands out in particular. The effects of catapult use on the morale of the enemy, particularly where artillery was used against combatants who had no previous experience of catapults or where major adaptations had been made to the types of engines being used also appears to be a significant overlap in the accounts.

Another common factor is that when catapults were used there was usually some form of physical barrier between the artillery and the enemy. In sieges, this was often the city wall (as well as any ditches, moats, barricades, or other defensive constructions which might lie between the city and the attacking force), but could also be the siege tower in which they were held, an embankment, or a stretch of water. In Arrian's *Ectasis*, the main body of the army separated the artillery from the enemy lines. Catapults were rarely used in situations where there was no physical barrier present, and are most commonly mentioned in accounts of sieges. This suggests that the catapults were vulnerable and they needed to be protected from the enemy. Given that in this period their main structural components were wooden, even if they were clad in iron, protecting them from fire-missiles and from enemy attack makes good sense. However, this may also tell us something about the speed at which they could shoot: perhaps the process of shooting the

963Cincius Alimentus, *BNJ* 810 T 4b = Livy, 27.28.13. See also above under 'Livy'.
964For defensive walls and the ways in which catapults were housed in cities in this period, see Marsden (1969), 116-163, and Winter (1971), 169, 231-3, 278-82, 284-6, 328-31
965See above.
catapult took enough time that a physical barrier was necessary to give some protection both to the machine and its operators. Catapults may simply not have been suited to face-to-face conflict.

More subtly, there are commonalities in what the historians do not tell us. Apart from Livy, none of the historians comments on how catapults were transported. None of the historians comments on whether catapults were moved during battle, unless they were already fixed to ships or mobile towers, which suggests that repositioning catapults was unusual once a battle or a siege commenced. It could be that it was too difficult to move a heavy catapult (which might need to be dismantled, have a large number of men shift it, or more machinery might be needed to lift parts of it); perhaps the overall scheme of the battle could be adversely affected by ceasing the shooting from a catapult in order to move it, or the operators could become vulnerable while moving the engines. Keeping the catapults in a fixed position during active fighting, therefore, seems to have been the usual, if unspoken, strategy.

The use of catapults for anti-personnel purposes (i.e. the disablement or death of defenders, or as a method of keeping attacking forces at a distance) is mentioned by Polybius, Livy, Diodorus Siculus, Plutarch, Curtius Rufus, Arrian, Sallust, and Timaios (in Diodorus Siculus). Experiments concerning range, accuracy, and penetration (including against shield and armour) can be used to test whether catapults could be used in this way. The effects on morale which catapults could have on opposing forces, mentioned by Livy, Diodorus Siculus, Nearchos (in Arrian), Plutarch, Curtius Rufus, and Arrian, cannot be tested safely under live-shooting conditions; however, a qualitative and experiential understanding can be gained from observing the catapults in action and their effects against armour, shield, and over distance. The frequency with which the catapults could be shot can be tested by timing individual shots.

Range testing can also be used to evaluate the claim made by Moschion (in
Athenaeus) that catapults could have a maximum range of up to 190m, though because of the danger of ricocheting missiles, the shortest range (as discussed by Livy, Diodorus Siculus, and Plutarch) cannot be tested safely. Questions about the positioning of artillery raised by Diodorus Siculus and Curtius Rufus can be analysed through range testing, accuracy, and experiential observations. How catapult bolts can affect armour and shields can be tested by shooting at these objects, and Plutarch's suggestion that a bolt could scratch armour at twenty paces, and Arrian's claim that bolts could pierce shields and stick in armour can be tested in this way. The portability of the catapults can only be considered though qualitative and experiential observations, i.e. how well and easily they can be moved.

The following chapter will consider in more detail how the tests were performed and what their results were in general terms, while the penultimate chapter of this thesis will discuss how the results of the experiments relate to the historians' descriptions of the use of catapults and the wider implications which that has on our understanding of the use of artillery in the ancient world. Before this, however, the literary nature of the authors discussed above must be considered.

Case study: Josephus

In addition to considering the ancient writers' accounts from a practical point of view, it is worth considering the literary aspects of their writing and comparing it to a later account of catapults in action. While this cannot help in answering the research questions of this thesis directly, since they focus on the need to test these machines practically rather than rehashing arguments based entirely on written evidence, such a case study can

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966This section has been placed after the summary of those writers whose work considers the Hellenistic period in order to mark out clearly that Josephus is not among the authors whose writings are being tested against the results of the experimental phase. The catapults in his Jewish War are significantly more advanced than the Hellenistic engines discussed throughout this period, and thus their performances cannot be tested using Medusa or Clytaemnestra. Please also note that the Whiston referencing system is being used in all of the references given below.
highlight areas where authors (particularly those who are not writing contemporaneously to the events described) may be using literary devices rather than describing catapults from their own experience or knowledge. It is important to note that it is only Josephus' literary style which is being considered in this section, and that while any claims he makes about the performance of catapults may be relevant to this discussion (in terms of comparing literary tropes) the alleged performances of the catapults themselves cannot be compared directly.

Josephus Bellum Judaicum covers the period 66-70AD\(^{967}\) and deals with the uprising against Roman rule which took place in Galilee.\(^{968}\) Much of its content is an eyewitness account from the author, who commanded one faction among the rebels.\(^{969}\) It was originally written 'in Aramaic' before being translated into Greek in around 75AD.\(^{970}\) The finished work was then presented to 'Vespasian and Titus'.\(^{971}\) As such, Josephus is closer to Polybius than the other authors considered above, since both wrote about contemporary events and, as non-Romans, wrote for a Roman audience.

Josephus explicitly mentions catapults at only six specific incidents in the Bellum Judaicum.\(^{972}\) However, in his long and detailed description of the siege of Jerusalem (70AD), Josephus mentions catapults on no fewer than fourteen occasions.\(^{973}\) Given his account of a comrade, standing beside him, whose head was stuck off by a catapult stone (at the siege of Jotapata in 67AD),\(^{974}\) it is perhaps not surprising that he should be so concerned about their use. Josephus' account matches that of the other authors in that he notes that artillery had a primarily anti-personnel function.\(^{975}\) This is particularly evident in

\(^{967}\)Smallwood (1981), 13.
\(^{968}\)Smallwood (1981), 9.
\(^{969}\)Smallwood (1981), 9 and 11.
\(^{970}\)Smallwood (1981), 14. See also Josephus, Bellum Judaicum praef.1.1.
\(^{971}\)Smallwood (1981), 15.
\(^{972}\)Josephus, Bellum Judaicum 2.19.9; 3.5.2 (positioning of artillery within the Roman camp); 3.7.9, 3.7.18, 3.7.23, and 3.7.30 (at Jotapata); 4.9.12; 5.1.3 (stasis in Jerusalem); 5.6.2-4, 5.7.2, 5.9.2-3, 5.11.5, 6.2.3, and 6.5.3 (siege of Jerusalem proper); and 7.8.6 (Masada).
\(^{973}\)Josephus, Bellum Judaicum 5.6.2-4, 5.7.2, 5.9.2-3, 5.11.5, 6.2.3, and 6.5.3.
\(^{974}\)Josephus, Bellum Judaicum 3.7.23. This account is a clear parallel to Livy, 29.7.6-7 – see above.
\(^{975}\)E.g. Josephus, Bellus Judaicum 5.6.2-3, 5.7.2-3. This use of artillery is discussed by Polybius, Livy, Diodorus Siculus, Plutarch, Curtius Rufus, Arrian, Sallust, and Timaios (in Diodorus Siculus) as discussed above.
an account from the siege of Jerusalem, where, as a result of defenders spotting where catapult stones were likely to hit (so as to avoid them) the attacking Roman forces blackened the stones in order to make them harder to see in the air. This account is not matched by any of the authors discussed above.

The incidents at which catapults are used in the Bellum Judaicum also echo the unspoken message from the authors discussed above that a physical barrier was always present between catapults and the enemy. As with the authors discussed above, these barriers usually came in the form of walls or siege towers. In particular, Josephus emphasises the vulnerability of catapults to being burned. Nowhere in the Bellum Judaicum are catapults used at river crossings or to defend passes (unlike in Arrian), nor is there any indication of their being used in a set-piece battle or from ships. However, Josephus also gives the impression that catapults needed to be raised up in order to achieve a decent range: platforms to elevate the artillery are a common feature of sieges in his account (especially at the siege of Jerusalem).

Unusually, Josephus, like Livy, tells us something about the transport of catapults from place to place. However, Josephus, like the other authors, fails to tell us whether catapults were moved during battle or not. Where he can be distinguished from the other authors (with the exception of Moschion in Athenaeus) is that he actually gives the specific calibre of some of the stone-shooting catapults at Jotapata and Jerusalem. Again like Moschion alone, Josephus provides a range for these catapults – in his case of two stadia, double the range stated by Moschion. Josephus also manages to improve on Plutarch and Arrian's claims about the penetrative abilities of catapult bolts, claiming that a

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976 Josephus, Bellum Judaicum 5.6.3.
977 Josephus, Bellum Judaicum 5.6.4, 5.9.2, 6.2.3 (like Plutarch, Livy, Diodorus Siculus, Sallust, Plutarch, Curtius Rufus, and Arrian).
978 Josephus, Bellum Judaicum 3.7.30, 4.9.12, 5.1.3, 5.7.2, and 7.8.6 (like Diodorus Siculus, Curtius Rufus, and Arrian).
979 Josephus, Bellum Judaicum 3.7.20, 5.6.4, 5.11.5, and 7.8.6.
980 Though given that there is no naval conflict of any kind in the work, this is not surprising.
981 E.g. Josephus, Bellum Judaicum 5.6.2 and 5.11.5-6.
982 Josephus, Bellum Judaicum 3.6.2.
983 Both 1 talent – Josephus, Bellum Judaicum 3.7.9 and 5.6.3.
984 Josephus, Bellum Judaicum 5.6.3.
single bolt could be shot pierce many men at once, though he does not tell us whether the
defenders in this case were wearing armour or not.\textsuperscript{985} Josephus describes catapult stones
breaking the corners away from towers.\textsuperscript{986} He also describes the effects of stones shot from
catapults on the human body, with a man's head knocked off his shoulders to a distance of three \textit{stadia} and a pregnant woman's unborn child flung from her body to a distance of half
a \textit{stadion}.\textsuperscript{987} These are extremely dramatic – even more than Arrian's accounts of Alexander
and a Sythian pierced through his armour, shield, and body by a catapult bolt.\textsuperscript{988}

The effects of catapults on the morale of the enemy is something else which is
considered by Josephus, and which mirrors the accounts of the authors discussed above.\textsuperscript{989}
The noise of the catapults is something which he highlights in particular.\textsuperscript{990} However, in
Josephus, the enemy against whom catapults are being used (the Jews or the Romans) is
not one which is unfamiliar with catapult technology (though during the siege of Jerusalem
it is clear that, at least initially, the defenders are inexperienced in actually operating their
artillery).\textsuperscript{991} As a result, on no occasions in Josephus' account is the enemy put to flight
simply as a result of the novelty of catapult technology.

Josephus' accounts of the use of catapults at sieges during the Jewish War tie in
closely with the other writers discussed above. His descriptions of the capabilities of
catapult bolts to penetrate defenders and of the effectiveness of catapult stones are more
gory and dramatic than anything in the authors who write about the Hellenistic period. The
range he gives for the one \textit{talent} stone-shooter is also an increase on that given by
Moschion. However, in most other respects, the \textit{Bellum Judaicum} significantly resembles
the other sources considered in this chapter.

The question therefore arises of whether the authors' general agreement is down to

\textsuperscript{985}Josephus, \textit{Bellum Judaicum} 3.7.23: ἥ τε ὀὖν τῶν ὀξυβελῶν καὶ καταπελτῶν βία πολλοὺς ἅμα διήλαυνεν...
\textsuperscript{986}Josephus, \textit{Bellum Judaicum} 3.7.23.
\textsuperscript{987}Josephus, \textit{Bellum Judaicum} 3.7.23.
\textsuperscript{988}Arrian, \textit{Anabasis} 2.27.2 and 4.4.4 respectively.
\textsuperscript{989}In Livy, Diodorus Siculus, Nearchos (in Arrian), Plutarch, Curtius Rufus, and Arrian.
\textsuperscript{990}Josephus, \textit{Bellum Judaicum} 3.7.9.
\textsuperscript{991}Josephus, \textit{Bellum Judaicum} 5.6.3 and 5.9.2.
literary convention or because catapults actually functioned and were used in the ways described. The two possibilities are not mutually exclusive. It is possible that, as part of a literary tradition, catapult use is described in this way because that is how artillery worked. There may well be some exaggeration on Josephus' part – particularly where he describes bolts penetrating several men at once, or the effects of catapult stones on the human body. However, these go beyond the level of damage described by Arrian and Plutarch, which suggests that this may not entirely be following a literary trope – he may have actually witnessed these things happening, may have misremembered as a result of trauma, or exaggerate deliberately. Without experimentation using the types of catapults in use at this point, it is impossible to know for certain which is the most likely possibility. However, given the results obtained in the testing phase of this project, it could well be that it is impossible to separate the literary tradition on artillery from the reality of catapult use to any meaningful extent; it seems likely that the two are entirely intertwined.

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992See below under 'Wider Implications'.
**Testing and Experimentation**

**Preliminary Testing**

The preliminary testing carried out on each of the catapults was intended to be qualitative rather than quantitative in nature. The main objective was to ensure that a shot could be taken intentionally each time the catapult was loaded and that each of the machines could be operated safely. A secondary aim was to make observations on how the catapults were and could be operated, for example examining how many people it took to reassemble the components of the catapults and then operate each one safely, and the effects achieved by altering the angles at which the catapults were shot.

The catapults were also observed for areas where frequent maintenance would be needed during their operation in order to assess their efficiency and reliability. The question of how often ropes would need to be re-torsioned was also considered. Additionally, the catapults were observed for any aspects of their performance which could be improved by slight adjustments and adaptations. Any unexpected aspects of the catapults' performances were also noted. How the catapults performed in comparison to the accounts of the ancient historians will be discussed in the following chapter.

**Medusa**

The testing of the stone-shooting catapult was beset with problems. As a result of the changing weather (especially humidity and temperature), the wood of the outer-framework beams swelled, making the spring-frame impossible to fit together.\(^{993}\) In order

\(^{993}\)It is likely that atmospheric conditions would have had an impact on the sinew in the spring-ropes had this material actually been used. Moisture can change the elasticity of the sinew and reduce the lifetime of a composite bow – Coulston (1985), 245, 248 and 270. He further notes that in composite bow construction 'Sinew is...the material most affected by temperature and humidity variations' – Coulston (1985), 253, and that the western European climate is perhaps not conducive to the use of this type of bow – Coulston (1985), 259. It is likely that these these conditions would be just as likely to affect the exposed sinew ropes of catapults. See also Rihill (2007), 279.
for the spring-frame to be assembled, it was necessary to enlarge the mortices and shave off the edges of the tenons on the outer-framework. However, when the temperature dropped the wood shrank and the holes became too large for the pegs. While there was not so much movement that the framework did not hold itself together while static, the looseness of the connections made the catapult particularly difficult to transport.

Moving the catapult into place required a great deal of effort. The spring-frame was too large to be carried by hand (being both too heavy and too bulky); the looseness of the framework was also a complication. The only way found to transport the spring-frame whole was on a forklift truck, face down, with the frame positioned by at least three people. The forklift could then raise the spring-frame to the height of the trestles, at which point the spring-frame could be rotated into an upright position and slid onto the trestles. It would have been extremely difficult to put the spring-frame together in place above the ground; it seems more likely that in the ancient world it would have had to have been lifted using a winch assembly.\textsuperscript{994} Even so, a large team would have been needed to assemble the catapult in the ancient world, despite this being a small stone-thrower.

By far the worst of the problems, however, was discovered when attempts were made to shoot the catapult. The forces which acted on the slider (the arms and bowstring pulling it forward, the winch pulling it backwards and upward) caused the slider to lift and twist out of alignment with the ladder. As a result, the slider was wedged between two rungs with its rear end lifted above the ladder and its front end twisted towards the operators. This was very dangerous for several reasons. First, the slider (and missile) were out of control. Second, the lifting of the slider meant that the pawl was not engaging properly with the ratchet teeth, which meant that the safety mechanisms would not work. Moreover, there was no obviously safe way to remove the missile once the catapult was in that position. In the end, the winch was very slowly and carefully slackened off to allow

\textsuperscript{994}See Wilkins (2003), 58: his Vitruvian stone-shooting catapult was initially lifted using this method, but the lift had to be completed with a 'modern crane...only when a faulty sheave block collapsed'.
the slider to move back into place; however, the position of the rungs of the ladder complicated matters, trapping the slider. These problems were exacerbated by the fact that despite the spring-frame being lashed into place, the ropes could not be made tight enough to prevent the movement of the slider and table forwards as the slider was winched back.

As a temporary solution, it was decided to fix steel brackets to the ladder, which would project over the edges of the slider without getting in the way of the trigger mechanism or the ratchet system. These were completely anachronistic, have no supporting evidence in the texts, and were chosen purely in an attempt to make the catapult safe for shooting in the hope that some quantitative data could be salvaged from the testing phase. The brackets were screwed into place so that they could be removed easily should another solution be found; they also needed to be removable because the catapult could not be disassembled with them in place. It was thought that by overlapping the brackets with the edges of the slider it could be prevented from lifting itself out of place or twisting out of its alignment. The next attempt to draw back the slider failed, however. The edges of the brackets cut into the bowstring, causing it to snap.

The second attempt to test the stone-shooting catapult with the brackets attached appeared to begin more favourably. The new bowstring, which had a longer stretch of serving, was able to withstand the brackets. The ratcheting system also worked well, with the pawl locking very strongly into the teeth as the slider was drawn back. The position of the winch in relation to the trestles on which the catapult was sitting limited the amount of withdrawal (i.e. retraction or pulling back of the slider) the operator could achieve before repositioning the winch bar, but because the ratchet system was working well this was not problematic. Unfortunately, after the slider had been drawn back by the distance of three of the ratchet teeth (approximately 33cm), the slider again began to lift, this time bending the brackets upwards. The pressure on the pawl was enough to bend

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995Figs. 44-46.
996Fig. 44.
997Fig. 46.
the bar which was holding it in place significantly out of shape. The slider became so wedged that the components had to be hammered into place again so that the slider could be carefully released; moreover the stress on the slider meant that the bowstring could not be released using the trigger. The slider and bowstring were both released very carefully, at a distance, and using tools to minimise the risk of injury to the operators.

At that point, it was decided that it was too dangerous to attempt to operate the catapult in its present state. The only way to make the machine safe would be to rebuild the slider and ladder completely, to incorporate a dovetail or similar joint to ensure that the slider could not rise out of position under any circumstances. Given the sheer amount of stress which was being placed on the slider from the winch and from the springs, a dovetail which was glued in place would not be sufficient: the joint would have to be fixed in place very securely to ensure that it would not break off and injure the operators. Under these conditions, it was decided to halt testing altogether, and use only the experiential data which could be gained from the testing up until this point. How these problems might be resolved in future will be discussed in detail in the conclusion of this thesis.

**Clytaemnestra**

The initial attempt to test the bolt-shooting catapult showed that the method used to fit the case and slider to the spring-frame was unsuitable and had to be changed (see above). A further problem was noticed at this stage. The way in which the trigger-box had been screwed onto the slider meant that the head of one of the screws was pushing against the pawl of the ratchet system. As a result, the pawl was not engaging with the teeth of the ratchet system properly, but instead was leaning out and away from the case. This was judged to be a safety problem, which needed to be dealt with before the catapult could be used. The quickest and easiest solution was to grind off the head of the screw, which

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998Fig. 47.
allowed the box to remain fixed in position. A more aesthetically pleasing solution would have been to remove the trigger-box from the slider and to countersink the holes before reattaching it. This would also have allowed the trigger-box to be removed more easily should further adaptations be required.

After these changes, it was possible to begin test-shooting the catapult. The ropes had already been torsioned while the spring-frame was on the ground, though an adaptation also had to be made to the torsioning bar as it had begun to bend under the strain. A piece of box-section steel was welded on to it to give it further support. The pins, which were intended to lock the washers in place after they had been turned were found to be too loose, and dropped out of the washers while the catapult was being assembled. However, this was not problematic, since the washers held themselves in position because of the compressive force caused by twisting the ropes. The pins were much more useful at the start of the torsioning process, when the washers were more likely to strain against them and try to return to a neutral position.

Initially, the shots taken were relatively inconsistent. These were made at a low power as a starting point, and the slider was only drawn back for the distance of two of the teeth on the ratchet system (22cm). Two problems arose: first, the trigger did not always release the bowstring when the trigger-bar was moved; second, when the bowstring was released, the missile was not released consistently. Approximately half of the time, the catapult mis-shot. The first problem was the easier of the two to solve. The 'claw' of the trigger, which pulls back on the bowstring, was removed and ground down. Its edges were rounded and smoothed, so that there was less friction acting on the bowstring, and to guide

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999See above.
1000The slider could be retracted by up to four ratchet teeth (44cm) to provide the maximum power available to the catapult, so this level of retraction represents half of the potential power which could be used. Unfortunately, the draw-weight of the catapults could not be established because the standard equipment used in archery (a bow scale) cannot be used on the horizontal plane, but can only be used with the bow suspended vertically, which was impossible in this case. Attempts to calculate the force of the propelled missile were also problematic, because the chronograph used was unable to register the missile (which was probably too large for a reading to be established). Calculating the velocity of the missile by timing its flight from the shot being taken to it hitting the target using video recordings was too crude a process for accurate measurements to be taken.
the bowstring smoothly away from the trigger when it was released.

The second problem was less easy to solve, since the action of the trigger was so quick that it was impossible to see with the naked eye why the missiles were not being released properly. After a series of further shots using different missiles, to check if it the bolts were causing the problem, it was noticed that the 'claw' on the trigger was striking the missile as it was released. As a result, the missile was knocked out of position, preventing the bowstring from striking it cleanly. The solution to this problem was to place the missile far enough forward that the 'claw' would miss it when the trigger was released, but close enough to the bowstring that the maximum power would be imparted to the missile.

During the construction phase of the project, the area around the 'claw' had been chiselled away, to allow it to sit deeply enough into the slider to grip the bowstring. By coincidence, the edge of the recess was just far enough away from the 'claw' to be able to mark where the back of the missile should be placed, and was close enough for the bowstring to strike the bolt cleanly and with the greatest possible force. To emphasise this positioning, the edge of the chiselled out area was outlined with a permanent marker, and several shots were taken with the bolts placed in that position. Each of the following shots was clean and consistent.

Having established a consistent method of shooting at a low power, the level of power was increased. When the slider was moved back to the length of three of the ratchet teeth (approximately 33cm), the shots were clean, consistent, and predictable. However, from that point on (i.e. from the length of three and a half teeth, approximately 38cm) the trigger began to release prematurely, and without human intervention. This was of great concern from both a safety perspective and with regard to the mechanical performance of the catapult. It was noted that this early release occurred sooner if the winch were being drawn back quickly; if it were done more slowly, the slider could be drawn back by up to four of the ratchet teeth before the missile was released. Because the early release was both
unpredictable and sudden, it was very difficult to tell what exactly was wrong with the trigger mechanism. Therefore, it was decided to film the early release so that, if necessary, it could be examined frame by frame to work out what was causing the malfunction.

This allowed the cause of the early release to become apparent: the pressure on the bowstring to move forward was pushing the front of the 'claw' upwards. The thickness of the trigger-bar should have been enough to prevent this, but it was also being pushed aside, which allowed the catapult to loose the bolt. There was some question as to how to prevent this. The recess in the slider which held the 'claw' could have been chiselled out further, allowing the 'claw' to sit lower and thus reducing the likelihood of early release. However, this was not guaranteed to work, and risked damaging the slider should the recess be deepened too much. A simpler solution was to turn the trigger-bar upside-down. This had the effect of presenting a higher bar on which the 'claw' could rest, because originally the trigger-bar had been recessed slightly to allow a smoother release. With this change in place, several more shots were taken at the higher power, with the slider retracted by four ratchet teeth (approximately 44cm). The malfunction did not reoccur.

This problem with the timing of the release is particularly interesting, however. If this fault were common, it is likely that the ancient engineers would have commented on it, even if it were an intentional part of the design. On the other hand, the ancient engineers might have expected it to be common knowledge, and so excluded it from their texts. Moreover, while for an experimental archaeologist who needs consistency in order to perform repeatable tests such an issue is problematic, on the battlefield and under siege conditions such a trait might actually be useful. As has already been noted, Philon did not consider pure repeatability to be a good thing; he notes that the target of the missile 'is not stationary, but liable to move out of the way'.1001 The ancient historians repeatedly tell us that catapults like this one were used as anti-personnel weapons during sieges,1002 and this

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1001Philon, Belopoeica 76.28: πρῶτον μὲν γὰρ οὐχ ἑστηκώς ἐστιν ὁ σκόπος, ἀλλὰ μεταχωρεῖν δυνάμενος (trans. Marsden). For full exploration of this subject by Philon, see Belopoeica 76.21ff.
1002See below.
is consistent with Philon's assessment. If a defender knew precisely (or even within a reasonable margin) where a catapult bolt was likely to hit, he could evade it. The unpredictability which is a problem for the modern academic would add a certain degree of randomness, making it harder for the enemy to estimate where and when a given bolt would strike. As a result, particularly in a siege, defenders would be forced either to take shelter or to accept a greater risk of heavier casualties. However, this problem could have an impact on the accuracy, range, and timing of the shot. This suggestion that unexpected releases were designed into the catapult is purely speculative. However, although there is no direct evidence from the ancient world to support this theory, the fact this occurred raises some interesting questions.

Philon does tell us that on single-shot catapults like this one each shot was aimed individually, but he does not tell us whether this was before or after the slider was winched back. Using the ratchet system, it is easier to aim with the slider retracted. Were the catapult to be aimed before retraction, which is possible with or without the ratchet system, an early or unexpected release would be less of a problem, particularly if the catapult were set at an elevated angle. In effect, the catapult would act as a 'semi-automatic' weapon, in the sense that it releases the missile itself (rather than the sense in which a missile is loaded automatically by the weapon, but the operator takes the shot). However, this is again speculation; it seems likely that consistency of shot would have been the priority for the ancient catapult operators, who would certainly have valued their own safety. Given that the technical treatises do not mention this, we cannot assume that the early release was an inherent part of the catapult's design. Therefore steps were taken to prevent the catapult from auto-shooting.

Following the correction of this safety problem, experimentation began with regard to the general range the bolts could reach. At this stage, no precise measurements were

1003Philon, Belopoeica 77.1-2.
1004See 'Section 2 – Building Clytaemnestra' above.
taken since the catapult was still in the very early stages of testing, and safety parameters were still being established. Moreover, the ropes were not fully torsioned, and so any detailed measurements taken at this stage would not have been representative of the catapult's capabilities. What was noticed was that (at this stage), increasing the withdrawal of the slider by one ratchet tooth (approximately 11cm) almost doubled the range of the missile when flat-shooting. The amount of force needed to winch the slider back increased substantially as it was withdrawn (i.e. pulled back). This correlates with this greatly improved range. For the distance of the first three teeth, the winch could be turned easily by hand; beyond this point, the winch became increasingly stiff and needed a lever to retract it fully. The increase in the range achieved seemed to reduce at the point where the slider reached the maximum withdrawal distance, though it was impossible at the time to say whether this was as a result of the range plateauing or because the rope-springs were beginning to stretch and lose power. Elevating the catapult also increased the range, again approximately doubling the total distance a missile could reach. This is something which would be tested further at the quantitative stage of the testing process.

One of the main objectives of this phase of the testing was to establish how many people were needed to reassemble and operate the catapult. Initially, four people constructed the catapult. First, the slider was fitted into the case, and two operators supported the case and slider assembly while another supported the spring-frame. A fourth person was then needed to fit and hammer in the wedges to hold the catapult together. The catapult was then lifted with one person supporting the case and slider, while two others lifted the heavier spring-frame. The fourth person guided the prong of the universal joint into position on the stand, and positioned the rest underneath the case. Great care was taken at the outset in order to avoid any damage to the catapult.

It was soon established that this level of care was unnecessary. In fact, it was possible to put the catapult together with just two people. One operator supported the case

1005A more detailed analysis of the ranges achieved at different settings is discussed below.
and slider assembly and lifted it to the correct angle, allowing the wedges to be fitted. The other supported the spring-frame and hammered the wedges into position. Using this method, the wedges could not be fitted as firmly as possible, but they were tight enough that the catapult could be lifted. Once the catapult was in place, the wedges could be hammered in more firmly. It was then possible for one strong person to lift the catapult from around where the universal joint is positioned, or for two individuals to lift the catapult with each at either end. When only one person was lifting the catapult, someone else was still needed to position the catapult on its stand. It was established, therefore, that when handling a catapult of this size a minimum of two people is needed for the catapult to be moved safely.

Operating the catapult also required very few people. Indeed, it was possible for one person to operate the winch and aim the catapult, while another moved the slider forward to allow the trigger to engage with the bowstring and placed the missile into position. The second operator was also useful in observing how far back the slider had been pulled, since from the position of the person operating the winch it was difficult to judge how far back the slider had moved. Having a single operator for the catapult proved impractical. The length of the case meant that the operator would need to move around the catapult in order to move the slider forward, and then return to the back of the catapult again in order to use the winch. It was possible for a single operator to aim and shoot the catapult, especially if the slider had been fully retracted. However, having a single operator initially had a poor effect on the aim. Leaning forward to move the trigger-bar pushed the catapult slightly out of position and meant that the bolt was more likely to miss its target. Later, an adaptation of the aiming method created an effective solution.\textsuperscript{1006} Having three people to operate the catapult was possible, but clumsy and unnecessary. If one person had the job of moving the slider to engage the bowstring, while another operated the winch, and the third released the trigger, it was possible to avoid obstructing each other. However,

\textsuperscript{1006}See below.
since the catapult could be operated with two people, another operator seemed superfluous.

Under the conditions of a battlefield or siege, this would no doubt be different. The catapult itself provides very little cover for the operators, who would have been vulnerable to attack. The catapult is also fairly delicately balanced on its stand, so that it could easily be pushed over from the side, while the ropes and exposed wooden parts are extremely vulnerable to fire and cutting. The historians note that artillery was frequently targeted by enemy catapults and sorties, and that raids were made against besieging forces in order to burn their catapults.\textsuperscript{1007} Possibly, extra men trained in operating the catapults would have remained close by or guards could have been placed on the engines. However, this vulnerability strengthens the implication in the historians' accounts that some kind of physical barrier was needed to protect engine and operators. It has already been established that catapults were expensive to construct and that they were viewed as investments, and it seems unlikely that they would have been left unprotected.

Over four testing sessions lasting between two and four hours each, the rope-springs were re-torsioned only once, between the first and second testing phases. There was no noticeable reduction in performance from the rope-springs over the final three sessions, which was a surprising result since it had been expected that they would need to be re-torsioned frequently. There was also little to be gained from re-torsioning the ropes, since they could only be twisted a further 90° (i.e. the distance between two of the pin holes in the washers). Moreover, the arms, which had been expected to have a short durability showed very little signs of wear. Small indentations were noticed where the arms struck the side-stanchions, in both components. These seemed to be signs of compression and did not appear to be causing damage. There was more wear visible where the notches in the arms held the bowstring in position, but, again, this level of deterioration was minor and did not affect the safety of the catapult's operation.

The component which needed the most maintenance was the bowstring. By the end

\textsuperscript{1007}See above.
of the first session, the serving at the centre of the bowstring had worn through, significantly weakening the string and making it dangerous and ineffective to use. It may be that the material was less suited to the task than the original sinew would have been, but without data for how sinew would wear in these conditions, it is impossible to be certain. A second bowstring was made for the later testing sessions with this in mind, and two extra layers of serving were added. The servings were also made considerably wider, to strengthen the centre of the bowstring and to ensure that all parts of the bowstring which were in contact with the slider or claw were protected. So that the level of wear could be readily judged, the outer layers of serving were black, while the centre layer was red. This layering seemed to have an incremental effect on the durability of each layer. The uppermost layer survived two testing sessions, while the centre layer began to show signs of wear by the end of the third session. The bottom layer remained intact.

The bowstring also stretched considerably during the catapult's operation. As the bowstring stretched and became loose, the amount of power which it delivered to the missile decreased significantly. Rihll comments that the bowstring 'is not (or should not be) taut when the catapult is at rest' without providing any evidence to support her claim, and in practice this does not make the catapult efficient. Her comment that this aids in stringing the catapult is also problematic. A loose bowstring seems more likely to slip off in operation (or even when a catapult is at rest), and the tight bowstring can easily be fitted even when the catapult is fully torsioned, although two operators are needed to complete the task: the bowstring is looped over one of the arms, and one operator pushes on that arm to move it inwards whilst the other operator slips the bowstring over the other arm. The same process is followed when twisting the bowstring further to counteract any stretching which may have happened during the catapult's use.

1008 See above.
1009 Fig. 63.
1010 See below.
1011 Rihll (2007), 280.
1012 Rihll (2007), 280.
At several points during the experiments, the cord which was used to winch the slider back snapped. It is worthy of note that the safety precautions put in place (the ratchet system on the side of the catapult) worked beyond expectations. Being made of pine, there was some concern that under pressure the ratchet teeth might be at risk of snapping, despite the care taken to work with the grain of the wood. However, when the cord snapped the ratchet teeth held the slider in position without any sign of strain being placed on the wood. The missile was removed safely and the energy in the bowstring was safely discharged.
## Initial Findings

Table 9: Initial findings

<table>
<thead>
<tr>
<th>Component/action</th>
<th>Finding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Washers/pins</td>
<td>The pins were only needed at the start of the torsioning process. Very quickly, the washers held themselves in position because of the compressive force and friction acting on them.</td>
</tr>
<tr>
<td>2 Operators</td>
<td>A minimum of two people is needed to reassemble and operate the catapult. More people could be useful to defend the catapult in the field and to replace injured or killed operators.</td>
</tr>
<tr>
<td>3 Re-torsioning of rope-springs</td>
<td>This was not needed as frequently as expected. Where further torsioning is done, the amount of twist which could be added was relatively small (less than 90º) and had little impact on the later performance of the catapult.</td>
</tr>
<tr>
<td>4 Arms</td>
<td>The arms showed much less wear than had been anticipated and were still in safe working order at the end of the testing sessions. There was a small amount of indentation where the arms strike against the stanchions, but this was minor.</td>
</tr>
<tr>
<td>5 Bowstring</td>
<td>The bowstring showed much more wear than expected. Even with a thickness of thirty strands of dacron and a layer of serving cord, the bowstring was subject both to wearing out quickly and to stretching during operation. The issue of wear could be solved easily by adding extra layers of serving to a new bowstring, while it was simple to re-twist the bowstring between shots.</td>
</tr>
</tbody>
</table>
**Further Testing**

**Clytaemnestra**

**Range**

The initial distance of the catapult from the target was 70ft (21.3m), which was about half the length of the available space. This range was chosen because preliminary shots had shown that the missile would certainly travel at least that far. The target chosen was a 4ft by 8ft (1.21m by 2.42m) plywood sheet nailed upright onto a frame. The slider was initially winched back by three notches (approximately 33cm), but this proved to have too little power for the missile to reach the target, even when the elevation was adjusted. At four notches (approximately 44cm), the missile was able to hit the target each time a shot was taken. This began with shots hitting the foot of the target but as the operators became more experienced the missiles began to land higher on the target and closer to its centre.

The target was then moved back to just over 95ft (28.95m) from the catapult. The missiles were able to reach this distance easily, with some adjustment to the angle of elevation. However, the scatter pattern of the missiles at this range was too wide for the bolts to hit the target. This was later established to be a result of the inexperience of the operators, rather than because of cross-winds or the instability of the bolts. The operators were able to make several shots pass by the target at approximately the same height, but although point of aim was consistent the missiles passed to either side of the target board. One bolt hit the target board at approximately the same height, almost dead centre.

Further testing was carried out at a later date, with an attempt to find the overall maximum range of the catapult. By this point, the method of aiming the catapult had been

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1013 Figs. 68-69. Plywood was chosen as a base material so that consistency could be achieved throughout the tests.
1014 See below, under 'Accuracy'.
improved and the operators had become significantly more experienced.\textsuperscript{1015} Because this part of the testing was carried out in wintry conditions, there was more crosswind than in the earlier testing phase. Moreover, in order to have the space to carry out distance testing and the ability to see exactly where the bolt hit (without the bolt skipping off the floor), the testing was carried out in a field neighbouring the original testing site. This was on much higher land, and for safety reasons shooting had to be done with the catapult aimed uphill against a gentle slope and away from nearby buildings, which may have very slightly reduced the overall maximum range, but probably provides a more accurate recreation of how catapults were used in the field. The maximum range achieved in this second testing was 94ft (28.65m) which is not significantly different from that achieved in level-ground testing. In these conditions, it was also possible to see that this was not exceptional; the longest shot achieved during the testing was part of a grouping which measured 10ft (approximately 3m) across, and had a difference of approximately 3ft (1m) between the shortest and longest distance.\textsuperscript{1016} The force with which the bolts struck the ground was significant, with some of them buried by up to one quarter of their length in the ground, showing that they had not lost all of their energy in flight and were still capable of doing significant damage.

This distance is significantly shorter than that achieved by Schramm,\textsuperscript{1017} but he does not specify which design of catapult (Greek or Roman) was used in his range test, and it seems likely that the Roman catapult, with its bent arms, would significantly out-range the Greek straight-armed design. Since Schramm's Greek catapults appear to have been built to a small scale, it seems more likely that it was his Roman engines which were used in the testing.\textsuperscript{1018} Perhaps more importantly, though, Schramm fails to tell us what the weight and lengths of missile he was using, if and how they were stabilised in flight, and what the weather conditions were at the time of testing. He also does not tell us whether his missiles

\textsuperscript{1015}See below, under 'Accuracy'.
\textsuperscript{1016}Figs. 70-71.
\textsuperscript{1017}Schramm (1980), 29-30. See also Marsden (1969), 86.
\textsuperscript{1018}Schramm (1980), 8.
were able to strike a target at the distances he gives, whether that was the point at which they struck the ground, and whether they skidded or stuck firmly; this is an important consideration when considering effective rather than possible range. By the time the missiles shot from Schramm's machines reached the ranges he cites, they might well (though because of his lack of detail we cannot know for sure) have lost their energy. This would render them physically (though perhaps not psychologically) ineffective against an enemy force. The effective range (i.e. the maximum range at which the missile is likely to do damage to its target) is therefore much lower, since significant force and speed is needed for the missile to pierce skin or break bone.\(^{1019}\)

**Accuracy**

Marsden talks at great length about the accuracy which he believes catapults could achieve even at great distances.\(^{1020}\) However, the majority of his evidence relies on the narratives of the ancient historians to be detailed, unbiased, and accurate or to assume that the 'twenty-five-pounder field gun' makes an accurate comparative model for field use of ancient artillery.\(^{1021}\) This seems to be putting the cart before the horse. Without testing the catapults themselves against the historians' accounts, we cannot assume that they are necessarily accurate, objective, or well informed.

The first stumbling block to achieving accuracy in shooting the catapult appeared when trying to establish a point of aim. There were two realistic options for sighting the catapult: either using the tip of the slider or the top hole-carrier as a sighting point. Either method could work but then it was necessary to work out how to sight the catapult in relation to the target. Initial shots aimed at the centre of the target at a distance of 70ft (21.3m) fell short or struck the very bottom of the board. Aiming higher, towards the top of

\(^{1019}\)Rihll (2007), 100-101. See also Karger et al. (1998), 495-501.
\(^{1020}\)Marsden (1969), 86-94.
\(^{1021}\)See especially Marsden (1969), 92-94.
the target, at the same range meant that the missile consistently struck the target at heights ranging from over three quarters of the way up (at 6ft 5in or 1.95m) to almost one third of the way up (2ft 10in or 0.86m). During this phase of testing, it was noted that the shot had a tendency to land further to the left than the operator was aiming. One bolt was particularly vulnerable to changing course, and was discarded.\textsuperscript{1022}  

Once the shots were striking the target board on each attempt, the accuracy which could be achieved with the catapult could be tested more quantitatively. To do this, a modern archery target (1m square) was attached to the target board, with the centre of the bull 5ft 10in (1.77m) from the ground.\textsuperscript{1023} This height was chosen to reflect the approximate height of a tall man in the ancient world (since Vegetius suggests that the height requirement for the Roman army was between 1.72m and 1.77m);\textsuperscript{1024} moreover, since the shots landing at this height were at a descending angle, those which hit the target could be assumed to be capable of striking men in the rank behind that represented by the target. 

Each of the two operators present for this phase of the testing took six shots at the target. Both hit the target sheet on four occasions, with five shots hitting within the rings. Six of the hits were to the right of the bull, with the remaining two striking the left side of the target. No hits were recorded in the bull, two hit in the next ring out, two in the following ring, one in the ring after that, with one in the outermost ring. One operator achieved a group within an area 20cm by 50cm, the other a grouping in an area 50cm by 60cm. These groupings were achieved after approximately one hour's practice with the catapult. Both operators were attempting to compensate for the drift to the left found during the earlier stage of testing, which may be the reason for the predominance of shots landing to the right side of the target. This makes it likely that the operators were

\textsuperscript{1022}It was later broken and mended, which corrected its inconsistency. The position of the bolt-head seems to have been at fault, since once the bolt-head was replaced the missile's performance improved dramatically.  
\textsuperscript{1023}Figs. 72-73.  
\textsuperscript{1024}Vegetius, 1.5.
struggling to aim the catapult initially, rather than an external factor (such as cross breezes) being to blame.

In part, this level of accuracy was established through the discovery of a phenomenon which appeared only when the catapult was fully torsioned and the slider fully retracted. At this point, the balance of the catapult shifted dramatically and set the catapult at what was established (through much testing) to be the correct elevation for that level of power. This point, which was nicknamed 'the sweet spot' by the operators, appeared when the centre of the winch was 84cm from the ground, a drop of 22cm from its position when resting on the stand (which gives the catapult an elevation of 11.64°). At lower angles (i.e. with the catapult shooting nearer to the flat) the missile might still hit the target, but lower; at steeper angles, the missile often fell short of the target. This has interesting implications for the catapult's use in the field. Clearly, from this testing, a catapult operator would not be able to shoot up at a wall or tower and be able to hit a target except at very close range. Marsden agrees that bolt-shooting catapults need to be shot 'at an angle much nearer the horizontal [than stone-shooting catapults]', and this experimentation bears out his argument.1025 This suggests that raising the catapult up (for example in a fixed position tower, on a wall, or in a siege tower) would be the only way to allow catapults to shoot elevated targets at a distance.

As discussed above, accuracy depreciated significantly over distance. At 95ft (28.95m), the only way to get the range for the missile to hit the target board was to hold the elevation just below the 'sweet spot'; this led to shots which would have hit halfway up the target had it been wide enough with a single shot hitting the target dead centre and 5ft 6in (1.67m) from the ground. It was not possible to hit the target with any greater accuracy, and so it was decided not to use the archery target, since striking the target at that distance seemed to be a matter of luck and crosswinds.

Interestingly, after further experimentation, it was discovered that sighting the

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catapult was not a requirement for accuracy and repeatability. One of the problems with sighting the catapult was that the operator often changed position between aiming and shooting the catapult. This moved the catapult slightly and affected the accuracy negatively. It was decided to attempt to counter this by not sighting the catapult at all. Instead, an appropriate elevation for the distance was established, and the operator noted where that elevation appeared on their own body. When shooting, the operator lowered the winch to that level, and then faced the target, thus pointing the catapult in the same direction. Over a short range, this led to one grouping (shot by an operator who is nearly partially sighted) which had three shots in line with each other over a distance of 13cm. During the second phase of range testing, this aiming technique was employed again, with the greatest range being achieved (along with a tight grouping measuring 10ft by 3ft (3m by 1m)) when the operator increased the elevation of the catapult to its maximum, in line with their knee while kneeling. This technique was, therefore, found to be a very time-efficient (since less time was taken in sighting the catapult) and accurate method of aiming. This would also allow an operator to be trained very quickly. Moreover, it shows that the operator need not even have good visual acuity: muscle memory could be used instead.

**Against Armour**

The armour used was a replica breastplate and backpiece. It was constructed from steel approximately 1mm thick, with a bronze wash, and could therefore be expected to be slightly stronger than the original iron breastplates. The armour was hung by its shoulders from one of the beams of the target frame and tied in place so that it could move slightly when hit, thus replicating the probable movement of someone hit by a missile. A bag filled

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1026 Figs. 74-75. To a degree, this aiming method seems to echo that seen on the Cupid Gem – see Fig. 14. This is a ‘carved gem from a finger ring’ showing a winged cupid operating what appears to be a *cheiroballistra* – Wilkins (2003), 43. Campbell suggests that it dates from the ‘first century BC’ – Campbell (2003b), 10.

1027 Fig. 71.

1028 For further details, see below under ‘Qualitative Findings’.
with rags was tied under the breastplate to represent the padding which would have been worn underneath, while its weight and bulk represented that of the wearer of the armour. This also added some weight to the assembly and resistance to both the bolt and the movement of the armour. Because the target was so small (relatively) and because there was a very strong chance of ricochet, the range at which the armour was tested was reduced to 40ft (12.2m), where a backstop could be placed behind the target and the area was enclosed sufficiently to prevent bolts from escaping.

This was the most difficult of all the targets on which to make a square hit. The curvature of the breastplate meant that several shots bounced off and only scratched or dented the metal, rather than piercing it. It was also the smallest of the targets used, which meant that fewer of the shots taken were actually on target; a large proportion of the shots taken went above the target altogether. A small medallion of Alexander the Great's head was fitted to the centre of the breastplate at the top of the chest, which was struck by one shot, which knocked it off cleanly. In total, seven good hits were recorded on the armour. Of these, two resulted in scratching or denting (but not piercing) the armour, one knocked the decoration off the armour, and four punched through the armour. Several shots bounced off the armour leaving no mark and could not be recorded, while some missiles hit the armour side on, having twisted in flight. Several missiles which missed the target hit the steel skip which was acting as a backstop (around five feet behind the target board) and left visible dents in the metal. None of the missiles which pierced the metal stayed in place once they had hit, although the bolt-heads penetrated the armour by at least \( \frac{1}{4} \text{in} \) (0.65cm). This may have been as a result of the padding which was placed under the armour not being close enough to the places where the armour was hit to 'catch' itself.

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1029 In other words the *linothorax* – this type of linen armour has been reconstructed by Aldrete et al. (2013). The reconstructed armour itself has been tested with regard to its defensive properties against arrows – see Aldrete et al. (2013), 91-128.

1030 Fig. 82.
1031 Figs. 80-81.
1032 Fig. 76.
1033 Figs. 76-81.
the missile. Another probable cause is that the missile simply did not penetrate far enough: had the missile pierced the armour as far as its widest point, it would probably have been caught by the armour itself.\footnote{Figs. 77-79.} The movement of the armour when hit, though limited, may also have absorbed a small amount of the missile's energy, thus reducing its impact.

While none of the missiles penetrated deeply enough to cause a serious wound, the force of each hit caused the armour to swing. This suggests that the missiles' power would be enough to knock a man to the ground, especially if he were already partially unbalanced (e.g. if he were moving to attack, turning, or off his guard). This would make the catapult a particularly effective weapon against defenders on battlements or attacking forces on a siege tower; it would also be effective against an enemy moving up or down a slope. If those hit by missiles wore little or no padding under the armour, it is likely that the missile would break the skin; the force of impact might also have been enough to cause bruising in someone wearing padding. In any case, the missile's impact would certainly be enough to throw a soldier off balance. It would clearly have a psychological impact too, and potentially increase his perception of his own vulnerability (though it could potentially have the opposite effect, by increasing his confidence in his armour to protect him).

**Against Shield**

The shield used consisted of bent plywood 97cm in diameter covered with a layer of canvas and painted. Again, because it was felt that there was a risk of ricochets and because there was such a small target area, the range chosen was 40ft (13.3yds or 12.2m). The shield was suspended with the beam of the target frame through the its leather strap. A large skip was used as a backstop, and the target was moved to position the shield centrally to it. Because of the way in which the shield was fixed onto the target frame, there was less room for it to move, which means that it replicated slightly less well the performance of a
shield under battle conditions.

It should be noted that more shots were on target than was the case with the armour, since it was a considerably larger target. In total, there were eighteen on target shots, with a main cluster of seven shots established at the top of the lambda painted onto the shield.\textsuperscript{1035} This grouping fits into an area of 14cm by 15cm. Other shots were more scattered, but none went past the leftmost point of the lambda, none went below it, two hit above the top point of the lambda, and seven were to the right of it.

Penetration of the shield was much more dramatic than it had been for the armour. Contrary to expectations, none of the missiles ricocheted off its surface, and none of the shots scratched the shield. All of the missiles which hit the shield penetrated at least as far as the socket of the bolt-head (i.e. 7cm), and some went slightly deeper (to around 8cm).\textsuperscript{1036} Those which only pierced the shield by 7cm were generally stopped by a fitting on the other side, such as those which held the handle in place or the leather strap.\textsuperscript{1037} The holes made by the missiles were slightly enlarged as the missiles were removed, and it was impossible to measure accurately their diameters while the bolts were embedded. The missiles were so tightly fixed into the shield that two of the bolt-heads remained embedded in the shield when their shafts were pulled free.\textsuperscript{1038}

Given that the missiles were able to pierce the leather of the strap, it seems very likely that they would have been able to penetrate living skin on the other side of the shield if they struck in the right place. Even if hits on the shield did not lead to direct injury to the man carrying the shield, the points of the missiles sticking though the wood would make it difficult for the user to continue holding the shield, since the bolt-heads, projecting through the shield, would catch on his clothing and armour. From experience of moving the shield after the testing, the author can attest to the fact that the bolt-heads which are stuck in the shield make it very awkward to carry. Moreover, the missiles projecting from the shield

\textsuperscript{1035}Fig. 86.
\textsuperscript{1036}Figs. 83-84.
\textsuperscript{1037}Fig. 85.
\textsuperscript{1038}Fig. 86.
would make it unwieldy. If the missiles were somehow removed from the shield, its structural integrity would no doubt be compromised, especially if it had been hit by a large number of bolts. Therefore, at this range at least, the catapult would be a highly effective weapon against men armed with shields.1039

Penetration

Penetration against the plywood sheet1040 was remarkably consistent. At 70ft (21.3m), out of eleven shots which hit the plywood board, all but one had a penetration of 7/8in (2.2cm) and one, which hit the bottom of the target (and was therefore plunging more than the other shots, which hit higher) had a penetration of 1¼ inch (3.2cm). At a range of 95ft (28.95m), the one missile which struck also had a penetration of 7/8in (2.2cm). It is worth noting that the plywood was wet and somewhat swollen, which may have reduced the maximum possible level of penetration,1041 but it is noteworthy that the level of penetration against the plywood remained remarkably consistent over the two distances.

Against armour, at a range of 40ft (12.2m), the bolt-heads penetrated by at least ¼in (0.65cm), but it was impossible to get an exact reading from the missiles, since they failed to remain in position once they struck the metal.1042 At the same range, against a plywood and canvas curved shield, penetration was much greater at between 7cm and 8cm, depending on the bolt-head and where it struck the shield.1043

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1039 For how effective this might be against closing troops, see below under 'Wider Implications'.
1040 See above.
1041 The level of penetration achieved against the plywood shield was significantly higher, though the thicknesses of the wood were similar. One notable difference was that the shield was completely dry and had not been exposed to the weather, which may imply that differences in penetration occurred because of the main target being swollen and damp.
1042 See above ('Against Armour').
1043 See above ('Against Shield').
The bolt-shooting catapult is very easy and simple to use. None of the operators had extensive knowledge of the practical use of this type of machine prior to this, yet within a matter of hours all three were able to hit a target at range repeatedly, and adjust the elevation of the catapult to find the appropriate angle for each distance. The operators were also able to adjust to some level of crosswind with a small amount of practice. Moreover, within a few shots, the operators were able to adjust to a small target (the armour) and were able to achieve relatively small groupings on a larger target (e.g. the shield). This suggests that with relatively little training, it would be possible to teach an operator to use a bolt-shooting catapult with enough effectiveness to be able to shoot at a group of attacking or defending forces with a reasonable expectation that they would be able to hit targets within a battle line or cluster of troops. Moreover, it would be possible for an operator with very little training to take over from a skilled operator with relative ease should the more highly trained man be killed or injured during fighting.

This can be taken further, since the operators discovered that sighting the catapult was not altogether necessary, and could even be detrimental to the accuracy of the shot. By using a combination of adjusting the angle of elevation from the position of the 'sweet spot' and changing body position, it was possible to hit a target repeatedly in a small grouping quickly and effectively. It was also possible for one operator to work out this position and explain it to another very quickly, while adjusting for each operator's height (i.e. what was at waist level for one operator might be at hip or stomach height for another). An operator would very quickly be able to learn which level of elevation, relative to his body, was best for given ranges. This 'point and shoot' technique would therefore be quicker and more effective in practice than attempting to line up each shot perfectly.

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1044 See above.
1045 See above ('Against Shield').
No speed test was undertaken because of safety concerns (especially after the winch cord snapped),\textsuperscript{1046} but from video footage, it is possible to show that a bolt could be loaded, shot, and the catapult reset in approximately 50 seconds. With the operators moving slightly faster, and with the use of a shorter rod (or fixed rods) in the winch drum, this time could potentially be significantly reduced. With less time taken to aim, using the physical aiming method outlined above, it would be feasible to suggest that a rate of three shots in two minutes could be achieved. For comparison, in the late medieval period a bowman 'could let loose six arrows' in 40 seconds, while an early handgun could fire a maximum of one shot in the same amount of time.\textsuperscript{1047} Nevertheless, this speed of shooting is consistent with Marsden's suggestion that a time of one minute is a more than reasonable 'time to allow for each aimed shot',\textsuperscript{1048} though his evidence for how he reaches assessment is sadly lacking.

Conclusion

Overall, the experimental evidence shows that the bolt-shooting catapult (as reconstructed here) was an effective and potentially deadly weapon. Over distance, accuracy was reasonable, but not all that could be hoped for. While its range was relatively short, it seems to confirm the evidence from the ancient historians that catapults would be elevated and protected by physical barriers.\textsuperscript{1049} The damage done both to the armour and the shield show that catapults, particularly if used en masse and against grouped opponents would have the potential to severely hinder an enemy attack or those defending a position. How the results obtained during this experimentation relate to historical evidence for catapults' use will be discussed further in the following chapter.

\textsuperscript{1046}See above.
\textsuperscript{1047}Esper (1965), 387.
\textsuperscript{1048}Marsden (1969), 94.
\textsuperscript{1049}For consideration of the use of defensive towers, see below.
Wider Implications

The following chapter considers the wider implications of the results from the testing phase and compares them to the ancient historians' accounts to assess how well they understood the use of catapults on the battlefield. To enable this to be done with as much clarity as possible and to avoid unnecessary repetition, the criteria against which the historians and the testing can be compared have been arranged thematically.

Anti-personnel use

In considering how catapults may have been used as anti-personnel weaponry, the tests which need to be considered are those of range, accuracy, and penetration (including the penetration of the armour and the shield). The historical accounts are clear that catapults were used to keep defenders off the battlements of their city or fortifications, but none of the historians suggests that there was specific targeting of individuals on the walls.\textsuperscript{1050} Likewise, in the case of defenders using catapults to keep attacking forces away from the city walls, there is little to suggest that individual soldiers were being targeted. On the rare occasions where we do have references to individuals being struck by catapult missiles, there is no direct implication that they were being targeted specifically,\textsuperscript{1051} though as they generally hold leadership roles (or are standing close to men with leadership roles) there is a hint that they may have been targeted individually. In all of these cases, there is no clear indication of the range at which they were shot.

The accuracy and range achieved by the bolt-shooting catapult in testing shows that individual targeting would certainly be possible at relatively short range (21m), and that at a slightly greater range (28m) individual targeting would still be just about possible.

\textsuperscript{1050}A much later example from the third century AD mentions specific targeting of individuals at the siege of Cremna – Zosimus, 1.7. See Campbell (2006), 187.

\textsuperscript{1051}Livy, 29.7.6-7, Plutarch, Demetrius 33.2 and 40.3, Arrian, Anabasis 2.27.2, 4.4.4, and 4.27.2.
However, at this greater range, the catapult would be able to target groups very easily, especially if the aiming techniques outlined above were used. Given that the ancient historians neglect to tell us the range at which individuals were hit, we can infer that their level of knowledge (or their belief that their readers would find such details interesting) is somewhat lacking.

Perhaps more difficult to explain is how the catapults could target defenders in elevated positions, such as on battlements. Tests with the bolt-shooting catapult established very quickly that raising the elevation of the catapult could be counterproductive. This suggests that the catapults themselves would have to be raised to allow them to target defenders on city walls. The fact that the ancient historians often describe catapults being used in conjunction with siege towers, on platforms on ships, or on raised earthworks shows that even if they did not understand the reason for it (something which they never explain), either it was common to raise catapults up in this way or that the historians knew that it needed to be done for artillery to be effective. This suggests a certain amount of reliability in their accounts.

The penetration which the catapult achieved against the armour and shield suggest that artillery could be used as anti-personnel weaponry. Given the force with which the armour was struck, it is reasonable to believe that the force of the blow could knock an enemy over, possibly even off a battlement or siege tower. Moreover, the force of the blow would be likely to cause internal injuries, including breaking bones and internal bleeding. The damage to the shield shows that the bolts were perfectly capable of breaking the skin even after penetrating the shield, since one bolt-head lodged tightly in the leather strapping. This tells us that, when in range, the catapults could make a highly effective anti-personnel weapon, in the way described by the ancient historians.

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1052See above
1053Fig. 85.
**Psychological effects**

Consideration of the psychological effects of catapult use depends greatly on qualitative and experiential evidence, rather than on hard data. It would be both unethical and dangerous to observe the catapult shooting from its target's position, and a camera's viewpoint would not adequately convey the feeling of being directly in front of one or more of these engines. However, even from the operator's viewpoint, it is possible to gain an insight into the psychological effects of catapult technology, and the information gained from the penetration tests on the armour and shield can also be useful. Moreover, standing in front of and at a distance from the unloaded catapult can give some insight into what it would be like to face one of these machines on a battlefield.

In order for the catapult to have such an effect on the enemy as to cause them to flee, artillery would have to be fearsome enough to break down the 'compliance relationship' which the army and its structures imposed upon the individual soldiers.\textsuperscript{1054} Where this is weak, we would most likely expect to see the occurrence of a rout or desertion of individual soldiers.\textsuperscript{1055} Moreover, we are also more likely to see soldiers fleeing the battlefield where troops are badly organised.\textsuperscript{1056} It seems likely that where the forces which run away from artillery (mainly where they have not encountered the technology before) are barbarians, the historians' intention is to emphasise the enemy's lack of sophistication and suggest that they are disorganised.\textsuperscript{1057} Though the historians probably did not have the concept of the 'compliance relationship' between soldier and army, the idea of a breakdown between the factors which encouraged the soldiers to fight (e.g. ideology, honour, coercive discipline, pay)\textsuperscript{1058} and those which made fighting considerably
unattractive (e.g. risk of injury or death)\textsuperscript{1059} provides a credible explanation of why a rout might occur. A weakening of this relationship, without reaching the point of a complete breakdown, would be a reasonable explanation for decreased morale. The question of whether catapults provided an intimidating enough effect to weaken or destroy this 'compliance relationship' must therefore be asked.

The size of the bolts is considerable. At 67.5cm long and 2cm in diameter, they are much heavier than arrows and much more visible in flight. A volley of arrows from longbows is highly intimidating; a volley of these missiles would be even more so, given that they would present a much heavier and darker image, especially if shot in large numbers. The size and weight of the missile would also be intimidating to a force which had not encountered catapult technology before, if only because they would not understand how the catapults were shooting such large missiles with such force. The machinery would also appear quite alien to them, particularly if the artillery pieces were large-scale.

The damage which the catapult managed to inflict, particularly on the shield and armour, could have a double effect, as discussed above. Although experimentation showed that the catapult had the capability to do serious damage to the shield and to pierce the armour (the force of which would be enough to cause internal injuries to the wearer even if the bolt did not pierce all the way through the skin), if the wearer of the armour and shield were hit but not injured, they could perhaps gain more confidence than they had previously. On the other hand, being hit by one or more catapult bolts, especially if they pierced the shield or armour would certainly be off-putting for the man hit, even if he were not injured. At the very least, the missiles would distract him from his task, while at most, it is likely that they would have the potential to put him to flight.

This could be exacerbated to a degree by some lack of accuracy over distance: a soldier would not necessarily be able to tell if a bolt were aimed at him, and he certainly would not be able to move out of its way while it was in flight. However, this would apply

\textsuperscript{1059}Crowley (2012), 19.
just as well to older forms of missile weapons, especially slingshot and arrows. Unless a soldier had no previous experience of artillery or it were significantly adapted to present a more terrifying front (as in the case of Archimedes' engines), it seems unlikely that missiles from catapults would bother him much more than missiles shot by hand, other than as a result of their size.

One aspect of the operation of the catapults which might very well add to their psychological effect on the enemy is the noise made when they are used. As the slider is withdrawn (i.e. pulled back), the entire engine compresses which results in the wood creaking and groaning loudly. When the triggers are released, the snap of the arms hitting the side-stanchions of the spring-frame is also impressive. Over open water and land, these sounds would carry well to the opposing forces, and as a result of the association between the sounds and the flight of the missiles, such noises could themselves have the effect of frightening the enemy. It has been noted that the *hysplex* mechanism which has been reconstructed also produces a 'characteristic sudden slap or bang' which would signal the start of a race (and thus have a psychological impact of its own).\(^\text{1060}\)

The ancient historians' suggestions that catapults could and did have the effect of terrifying those against whom they were used can therefore be considered reasonable to make, particularly when they were used against forces which had never experienced artillery previously. Moreover, the historians' descriptions may well have increased fear of catapults by encouraging their readers to view catapults as a frightening battlefield technology.

\(^{1060}\)Valavanis (1999), 45. See also above – 'Introduction'.

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Positioning of artillery

Being able to judge where artillery needed to be positioned was clearly an important aspect of the use of catapults, since once in position the larger engines in particular would be very difficult to move. Moreover, a general would need to know where to base his troops, artillery, and other siege equipment based upon where the enemy's catapults were located. Without this level of knowledge, it is likely that an attacking force would suffer high levels of casualties.

Again, because of safety concerns, it was not possible to examine this from the viewpoint of those opposing an established catapult battery. However, there would be several ways for a general to find out his opponents' catapult range. If he were already familiar with the size and type of catapults owned by the city, his own experience of how such catapults worked should allow him to estimate their range. Alternatively, he could wait for them to start shooting at his forces and judge their range based on where the missiles fell. A third way for him to estimate the range of the enemy's artillery would be to make a guess based on his own experience with his own machines. Catapults in siege towers would be at a similar height to those positioned on the city walls, and so his experience ought to provide him with an approximate range.

From the defenders' point of view, their artillery was most likely already in a fixed position within artillery towers. Towers to house catapults appear to have been in existence from early on in the catapult's development, and examples of towers with apertures of various sizes through which catapult operators could shoot, while scarce, do exist in the archaeological record. Ober notes a much larger number of these towers than the two ('Perge and Side in Pamphylia') mentioned by Marsden. Problems with dating these

1061 See below under 'Portability'.
1064 See below. See also Milner (1997), 211
towers occur frequently, and it is often necessary to rely on the 'style of masonry' in order to estimate their date of construction. Surviving towers which retain evidence of apertures for artillery include the 'Mazi Tower' in Attica (dated to the mid-fourth century BC), which has indications of 'a large shuttered window...in the west face of the tower' at the level of the fourth storey from which Ober suggests catapults would have shot, 'Tower F' in the 'Vathychoria Region' of Attica (dated to 'the third quarter of the fourth century') which has large windows approximately 1m which Ober suggests were used for 'catapult fire', the 'Aegosthena' tower in the same region (dated to 'the second half of the fourth century or possibly the early third century') with 'three catapult windows (ca. 85 x 120 cm)' set in the fourth storey, and the towers at 'Heracleia on Latomus' which could hold several catapults 'on each floor'. Other examples include 'Messene, Tower N' (dated to 'the early second quarter of the fourth century') which has windows suitable for catapults on three sides and which could hold four gastrophetai or three 'stand-mounted' catapults, and 'Messene, Tower L' which could have held catapults in an upper and lower chamber and is similar in the design and layout of its windows to 'Tower N'. The small size of the windows in these latter examples suggests that forms of the gastrophetes may have been used in them rather than the more developed

1069 Ober (1985), 164. NB: Place names here are given in inverted commas to allow easy direct referencing with the authors cited in footnotes, and to allow for consistency in the spelling of place names by the author of the thesis here and elsewhere.
1071 Ober (1985), 167. Ober's phrasing is, of course, somewhat misleading – the term 'fire' applied when missiles are shot should only be used in the context of firearms (e.g. where gunpowder is used). Variations on the word 'shot' would be more appropriate here.
1073 Ober (1985), 168.
1074 McNicoll (1997), 75-81.
1075 McNicoll (1997), 79.
1076 Ober (1987), 572-574
1077 Ober (1987), 573.
1078 Ober (1987), 574.
1080 Ober (1987), 575.
torsion catapults which may have been used in those towers with larger windows. The 'Mazi Tower' also has 'arrow slits' built into its walls from the second storey to the fourth. These could, potentially (though there is no direct evidence to prove this), be used in conjunction with the hand-held *gastraphetes*. 'Arrow slits' are also found, for example, in the tower at 'Gyptokastro, probably ancient Eleutherai' (dated to 'the first half of the fourth century', but with finds of pottery dating to the Hellenistic and 'early Roman' periods), 'Tower C' in the 'Vathychoria Region' of Attica (dated to 'the third quarter of the fourth century') and which 'may have been adapted for small catapults', and 'Tower F' and the 'Aegosthena' tower in the same region. Examples of towers from Boeotia with surviving evidence of potential catapult use include 'Siphai, Tower 3', (dated to around 371-362BC) which has windows suitable for catapults on two sides and which Ober suggests was designed for catapults similar to those in 'Messene N', and the 'Siphai, Sea Gate Tower', which may have had a window for a single catapult along with 'arrow slits'. These towers would certainly have raised catapults up enough to create a great improvement in the ranges they were able to achieve, especially where either the catapults were placed several storeys above the ground or the ground in front of the walls of the tower formed a steep downwards slope. This would have important consequences for attacking generals when attempting to position their camps outside of catapult range.

Based on the experiential part of the experimentation, it seems very likely that

1082 Ober (1987), 574.
1083 Ober (1985), 156. See also Ober (1987), 589-591.
1086 Ober (1985), 166.
1087 Ober (1985), 165.
1089 Ober (1985), 168.
1091 Ober (1987), 577.
1092 Ober (1987), 578.
1093 Ober (1987), 580-582.
1095 Ober (1987), 574, Marsden (1969), 117-118 and 117 Fig. I, and McNicoll (1997), 79.
catapult operators would quickly become familiar with the ranges they could expect from their machines. They would perhaps be able to advise their commanders about where catapults would have the greatest effect. This is not mentioned by the historians, however. It might suit their narratives better to focus on the general and his aides much more than on soldiers at a lower level unless they were doing something particularly interesting. A paragraph discussing how the engineers advised their leader on the siting of catapults probably would not fall into that category for the historians and their readers, and so such details are likely to be omitted. However, the experiential information gathered suggests that being able to adjust the catapult to adapt to different ranges is relatively straightforward for the operator. Therefore, it seems likely that armies would be able to judge catapult range, though whether individual generals were able to is questionable. The historians' accounts are once again limited by their lack of detail, and it seems likely that while they had knowledge of armies staying out of artillery range, they were uncertain as to how this was achieved.

Longest range

Given that the catapult described by Moschion was approximately seven times larger than the catapult built for this thesis, it is perhaps not surprising that Clytaemnestra's range was significantly shorter. It is highly unlikely that catapult bolts would be accurate over the range suggested by Moschion (190m), given that accuracy was initially significantly reduced at just under 29m distance from the target in the first round of range testing. It seems incredibly unlikely that the catapults Moschion describes could shoot effectively at that range, especially given that the operators probably would struggle to pick out a target at that distance; when crosswinds are taken into account, Moschion's range seems even more unlikely. This range was, however, achieved and bettered by
Schramm, though as discussed above it is unlikely that he was using a comparable catapult. Further research is also needed as to how height above ground affects the range which catapults can achieve, since it is clear from the historians' accounts that catapults were most often deployed from earthworks and siege towers, something which could not be tested during this thesis owing to both safety concerns and a lack of resources.

The range achieved also appears to confirm the evidence from the historians that catapults were used mostly in static or fixed position combat situations. The range appears to be quite short in comparison to the ranges achieved by Schramm, but if heavier bolts were used in these tests then they may well have lost energy more quickly in flight. Nevertheless, a heavy object moving quickly, even if it has a relatively short range, can still do a great deal of physical and psychological damage to an opposing force; moreover the distance achieved is 1.7 times greater than has been achieved in experiments with Greek javelin throwing (where lighter sporting javelins, which would be expected to travel further, were used). It is likely, then, that catapults were able to out-range javelins even at the lower than expected range found during these tests. This would make them effective in the types of combat settings in which the historians described them, if not in a set-piece battle.

Portability

The unspoken suggestion implicit in all of the authors' works that the catapults, once in set in position, were unlikely to be moved is one which makes a great deal of sense. Even though it proved impossible to generate results from shooting the stone-

1096See above. See also Schramm (1980), 29 and Marsden (1969), 86.
1097For consideration of defensive towers, see above.
1098See below.
1099The distance achieved by the javelin throwers was 54ft (16.62m): see Harris (1963), 34. For information about the javelin used, see Harris (1963), 27 and 31.
throwing catapult, the engine itself was set up several times. The bulkiness of the engine, combined with its weight, meant that it was very difficult to set in place. Using ancient technology to lift the spring-frame into position would leave those working to erect it extremely vulnerable to enemy attack. Moreover, the catapult built for this thesis is one of a relatively small scale; Philon tells us that the diameter of spring holes could reach twenty seven dactyls (52.11cm) for a three-talent engine, significantly larger than those in Medusa.\textsuperscript{1100} Such catapults would be incredibly unwieldy to put together in the field, and they would be very difficult to move once erected.

On the other hand, it was discovered that the bolt-shooting catapult was very easy to move once the spring-frame was attached to the case and slider. With one or two operators lifting the bulk of the catapult and another moving the stand, the catapult could be very easily repositioned. However, given the need for the catapults to be raised up and that they were often used along with siege towers,\textsuperscript{1101} it seems unlikely that they would have been moved individually during sieges. The fact that the historians do not discuss the movement (or lack thereof) of catapults on the battlefield at all, however, shows a decided lack of interest in this aspect of their use. Those with military experience may have known whether catapults, once reassembled, were repositioned, but as none discusses this, it seems that we cannot assume that they actually had any knowledge of whether this was done on the battlefield.

An important aspect of the design of the catapults is that they can easily be broken down into small components to facilitate easy transportation. Livy's suggestion that they could be transported in wagons therefore makes sense.\textsuperscript{1102} There is a distinct lack of interest among the other historians in how artillery was moved, however. The details of a baggage train, unless it contained some glorious treasure, probably did not appeal to the historians' sense of what their readers would find interesting and exciting, yet it is notable that

\begin{footnotesize}
\begin{enumerate}
\item Philon, Belopoeica 51.21-26.
\item See above.
\item Livy, 42.53.4.
\end{enumerate}
\end{footnotesize}
although they tell us that catapults were used by the same army at sieges far distant from each other, the historians give us no indication of how they were transported, and only rarely tell us that they were constructed from scratch in the field. Again, this lack of interest does not tell us that the historians were unaware of the logistics of transporting catapults, but in this case only Livy can be judged against the experimental evidence which shows that catapults could be broken down for transport, and that components like the spring-frame did not have to be permanently fixed together in order for the catapult to be operational.

**Damage to armour and shield**

The damage to the armour was fairly consistent with Plutarch's description. The shots taken against the armour were at a range just short of twenty Greek or Roman paces, and the armour was scratched and dented by several of the shots. The skip which was used as a backstop was also scratched and dented by the shots which missed the main target. However, the damage to the armour was, overall, more significant than the small amounts of damage caused to the armour in Plutarch's account. The missiles were able to pierce the metal of the armour completely in several places, rather than just marking the outside. Plutarch does not tell us the material from which the armour was made in the test he describes, nor its thickness, nor the calibre of the catapult which was used. The experiment does show, however, that it is possible to create the same effect using a catapult against armour, which means that Plutarch's description can be considered moderately reliable, though his lack of detail renders his account somewhat limited.

Arrian's claims that a catapult bolt could pass cleanly through shield, armour, and flesh seems less reliable than Plutarch's account of the catapult bolts scratching armour,

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1103See above.
1104Plutarch, *Demetrius* 21.3.
1105Dilke (1987), 26-27. See also *LSJ* under βῆμα.
however.\textsuperscript{106} In testing, although the body armour was pierced, even without further protection the bolt did not stick or pass far enough through the metal to stick in the skin. Moreover, when shot at the shield, although the bolts passed through and stuck, the penetration only went as far as the top of the socket. This meant that the tips of the bolt-heads were in alignment with the edge of the shield, but did not penetrate any more deeply.\textsuperscript{107} As a result, while the bolt-heads could have penetrated the arm of the man holding the shield, they would have been kept well away from any body armour he was wearing and would not have been able even to strike it, much less pierce it. Through a lighter shield with less curvature, a strike into the shield might well be able to continue onto the body armour. However, the plywood of the shield absorbs the majority of the force exerted by the missile, and so very little damage would be done to metal armour underneath. Arrian's account, therefore, appears, based on the experimentation, to be somewhat over-dramatised. It may be that the more developed artillery of his period was capable of achieving the results he describes, but the Hellenistic catapult is unable to replicate this effect.

\textbf{Speed of shooting}

The speed with which the bolt-shooting catapult could be shot is, as discussed above, comparable to the rate of fire of an early handgun, or approximately six times slower than a longbow in the late medieval period. This is certainly not fast, and a bank of catapults would therefore be needed to provide large enough volleys to hold back an approaching force. Even with a large number of catapults, the rate of shooting is still low enough that it is likely that few hits would be made between the enemy entering missile...
range and coming close enough to the catapults to do them and their operators damage. Having extra soldiers to defend the catapults and their operators might slow down an enemy's approach, as might caltrops (and the double-pointed spikes which were used in this period) scattered on the ground, although there is no literary evidence of their use in conjunction with catapults in this period.

This suggests that the general evidence which can be gleaned from the literary sources may be correct, since at the vast majority of the incidents at which the historians mention that catapults were used there was some kind of physical barrier between the catapults and the enemy. As a corollary to this, the fact that catapults took a long time to shoot and reload would explain why catapults are so rarely seen in the literary sources being used on open battlefields, since without some kind of barrier between them and the enemy they would be highly vulnerable to attack. None of the historians explains this, and so it seems likely that to them, this was just how catapults were used; this again indicates that the historians may have had a good knowledge of how catapults were used, but without a detailed understanding of why they were used in this way.

Conclusion

Overall, the historians' accounts seem to be fairly accurate as far as they go, with the exceptions of Arrian, whose claims with regard to catapults' penetrative capabilities has been shown to be wildly exaggerated, and Moschion, whose suggestions of range appear to be greatly misleading. Although limitations to the results of the testing phase exist (in particular because of the choice of rope used in the catapult springs and the difficulties encountered because of the limits to the available areas for testing the catapults) the qualitative nature of the ancient evidence means that strong conclusions may be drawn by comparing the experimental data to the data gathered from the ancient sources. Very little

1108Bishop and Coulston (2009), 69-70.
of the ancient evidence has a quantitative element, and therefore it is the experiential (i.e. qualitative) information obtained through the experimental phase of this project which is more directly comparable to the information given by the ancient authors. Where quantitative evidence does exist in the ancient sources, care was taken to ensure that conditions were as closely replicated as possible to those described within the source. While with sinew rope the penetrative effects could potentially have been improved, it is not considered that there would be a level of difference significant enough to have an impact on the findings of this chapter.

All of the historians' accounts are severely limited by a lack of detail, which suggests that the historians generally tended to have a reasonably believable impression of how catapults were used in the field, but did not understand why artillery was used in particular ways and the reasoning behind when and if it was used. The historians tend to simplify their accounts, perhaps because they felt that the technicalities of using artillery would be uninteresting to their readers, or perhaps because they themselves did not understand the principles behind how catapults were used. There is also the risk of exaggeration in the historians' narratives. It is certainly more dramatic to have a man hit by a catapult bolt through his shield, body armour, and flesh than for the missile only to penetrate one, or at most two, of these layers. The historians can, therefore, be relied upon up to a point; however, their reliability is limited by lack of detail, simplification, and, at times, dramatisation.
Conclusion

Up until this point, the body of literature on ancient artillery has been very limited. Those works which do exist focus primarily on text-based approaches to understanding the role of catapults in the ancient world or include only a small amount of archaeological evidence.\textsuperscript{1109} Others, on the other hand, such as Schalles' edited volume on the Xanten manuballistra\textsuperscript{1110} focus entirely on the archaeological evidence with little room to consider the literary tradition of the artillery manuals or the role catapults played in the historians' writings. The majority of large-scale reconstructions which have been made of catapults focus on the Roman period,\textsuperscript{1111} while the Hellenistic period has been left relatively unconsidered for experimentation.\textsuperscript{1112}

This thesis contributes to scholarship not only by extending this body of work, but by filling in the gaps left by its predecessors. By choosing to focus on the Hellenistic period, it brings an unexplored area of research to light and raises questions of reliability amongst the ancient sources which have been ignored by earlier scholars.\textsuperscript{1113} The practical part of this thesis has also raised the question of how to deal with the gaps in the texts of the technical authors whilst maintaining a building process which is as true to their original designs as possible, something not discussed by previous scholars. Moreover, this thesis has contributed to the methodological approach of experimental archaeology by showing that a method which combines text-based research with archaeological evidence to produce a functioning replica is a sound way to consider ancient evidence.

This work has sought to answer three main research questions: first, is the use of

\textsuperscript{1109}E.g. Marsden (1969) and (1999), Rihll (2007), Baatz (1978) and (1994), and Cuomo (2002) and (2007).
\textsuperscript{1110}Schalles (2010).
\textsuperscript{1112}It should be noted, though, that Schramm did construct small-scale models of early artillery in the early twentieth century. See Schramm (1980), 8.
reconstructions, based on technical treatises and archaeological evidence together, a
suitable way to approach the question of the reliability of the ancient historians who wrote
the military history of the Hellenistic period? Second, using this methodology, what can we
learn about the historians' reliability in their narratives where catapult technology is
concerned, and does this have wider implications for our understanding of how artillery
was used in the ancient world? Third, what can the reconstructions themselves tell us about
catapults and their use on the ancient battlefield?

In order to find the answers, related investigations have had to be carried out. The
first section of this thesis considered the technical authors, with particular reference to their
practicality and the level of technical information which they provide. They were assessed
in terms of their suitability to provide the basic framework of instructions on which
reconstructions could be based and in terms of their approach to the most technical aspects
of artillery construction. The second part of this thesis focussed on the building methods
used to construct the catapults themselves, and on the ways in which problems in the texts
could be resolved to allow the catapults to be built accurately and effectively. To some
degree, the final part of this section overlapped with the testing phase in the final section of
this thesis, since the early testing of any machine and slight adjustments at the end of its
construction go hand-in-hand. The final section dealt with the testing of the catapults and
comparison of the results of this experimentation with the accounts provided by the ancient
historians.

This conclusion will summarise the findings of each section, ending with a
synthesis which brings together all of the insights gained over the course of this research
project to show how the research questions have been answered. Any areas where lessons
have been learned with regard to this methodology will be highlighted, and suggestions as
to how this research may be extended, improved, or used in future work will be discussed.
This section of the thesis analysed each of the works of the three main technical authors for this period (Heron, Biton, and Philon). The main finding was that, of the three Greek authors, Philon was by far the most technical and practical. His *Belopoeica* was the most systematic of the three treatises, moving from the historical background of catapult design to the usual design for torsion engines, and then on to more novel catapults designed by himself and other craftsmen. Moreover, his treatise had a highly consistent technical vocabulary and used instructive language throughout which pointed to his intended audience being made up of specialists. Philon's work also demonstrated that he personally had a great deal of practical experience in catapult construction, to the point where, after describing the torsion catapults which were in general use in his time, he gave his readers details of a catapult he himself had designed to overcome what he saw as flaws in the pre-existing models.

Additionally, Philon's *Belopoeica* was the only one of the three Greek treatises to contain a detailed description of the proportional system of measurements by which catapults of different calibres can be constructed from a single basic measurement (the diameter of the spring-hole). Without these measurements, it would be impossible to build a catapult of this period from scratch, since the archaeological remains consist primarily of the washers (which give us the diameter of the spring-hole) and not the actual frame of the engine.\(^{1114}\) This alone would make Philon the most practical and useful of the treatises, but when this is placed in the context of his extremely technical writing style and his own practical experience, his treatise is by far the most serviceable.

Biton's *Construction of War Machines* was by far the least useful of the three. Nevertheless, some interesting results arose from the analysis of Biton's text. He demonstrated absolutely no practical working knowledge of the construction of artillery,

\(^{1114}\)For the one wooden spring-frame which survives from a later period, see Schalles (2010).
but he did provide measurements for his catapults (though these were fixed, rather than proportional, dimensions). Most interestingly, the structure of Biton's work is set out as a chiasmus, \(^{1115}\) with a discussion of two catapults, followed by descriptions of two engines for reaching the top of city walls, followed by a discussion of two more catapults. This structural detail seems not to have been noticed by scholars previously. However, it marks the treatise out as a literary construction, particularly when considered alongside the work's lack of technicality and the tentative nature of Biton's instructive language.

It was decided to set aside Biton's treatise, since it had little practical use for this project (though his recommendations for particular types of wood for catapults were considered in the following section, along with the other two authors' suggestions), and to focus primarily on Philon and Heron's works. Heron, despite not providing measurements for the components of his catapults, does at least offer descriptions of them, and these combined with Philon's work were able to provide almost all of the details which are necessary for the reconstruction of Hellenistic catapults.

**Building the catapults**

This section was primarily concerned with describing and explaining how the catapults (and ancillary items) were constructed and manufactured. The first part of this section considered the tools and methods for the building process. The majority of the tools selected for the work either had direct equivalents in the ancient world or were electrically powered versions of the tools available to ancient carpenters. Much of the evidence for the types of woodworking equipment in the ancient world came from the archaeological record, with some evidence from relief sculpture and other pictorial representations. The materials chosen for building the catapults were also discussed, and were chosen to be as close to those used at the time (based on the technical authors' recommendations and the

\(^{1115}\)See above, pages 34, 88-89, and 95.
archaeological evidence) as possible. The use of inauthentic equipment (including, for example, screws) was explained and justified.

An additional part of this section focussed on the materials used for the rope-springs. Very little research has been done on the performance of sinew and horsehair ropes. Of what has been done, the majority has been performed for documentary makers with only a small portion being done for academic purposes. The data which has been gathered is largely unavailable. The information which does exist points to nylon as being the closest equivalent synthetic material to sinew in terms of its performance under elasticity and weight-bearing tests. In consequence, this was the material chosen for the rope-springs for both catapults.

The second part of this section focused on the building of the stone-shooting catapult, which was named Medusa. This catapult was very complicated to construct, having around three times as many individual wooden components as the bolt-shooting catapult. Problems were encountered almost immediately in trying to ascertain the shape of the hole-carrier. The descriptions of the methods for making a template for this component in Heron and Philon's texts both lacked important details; however, by combining the usable information from both treatises, it was possible to create a template which fitted Philon's criteria. The next problem arose with the design of the 'counter-plate' (the ὑπόθεμα), since Philon only provides its thickness. Without another text to use as a comparison (since in Heron's Belopoeica, the ὑπόθεμα serves a completely different function, and Vitruvius has no equivalent component), innovation was needed. As a result, a novel solution was offered, which also solved the problem of how the outer-framework beams were attached to the spring-frame. Marsden had offered a vague solution to the latter problem, which seemed to be simply to fit the frame around the two half-springs firmly, but given the amount by which wood can expand and contract depending on the

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1116 See above under 'Building Methodology – Building Materials, Ropes' for further details.
1117 Marsden (1969), 32.
atmospheric conditions, it was argued that this method was both impractical and unlikely to work. The solution which was found for the ὑπόθεμα also allowed tenons to fit through mortices in the outer-framework to hold it in place.

At the testing stage, however, the stone-shooting catapult experienced problems with the slider rising up during shooting. This was so dangerous that testing had to be halted, and inauthentic safety measures (brackets to hold the slider down) were added to the ladder. Unfortunately, these were not enough to correct the issue, and during the next attempt to shoot the catapult the same problem arose, with the forces acting on the slider causing the brackets themselves to bend out of shape. The bar which held the pawl of the ratchet in place was also put under a dangerous amount of strain. Testing on the stone-shooting catapult was therefore halted completely. The problem seems to arise from a confusing passage of the text, which refers to a component which Marsden translates as 'ridge-poles' (πτερύγιον). Several methods had already been tried to fit this component into the design of the catapult, without success. Philon gives us all of the proportional measurements needed to construct the component, but does not explain how it fits into the overall construction.\footnote{1118Philon, Belopoeica 54.12-13.}

Attempts were made to use the component to hold the slider in place, but these interfered with the movement of the slider and the function of the trigger mechanism. Marsden's assertion that the component should be interpreted as a kind of dovetail joint does not fit in with the description made in the text,\footnote{1119Marsden (1999), 162, Figure 4. See above for discussion on why this was not done during the building phase.} which makes no mention of the component being cut on an angle.\footnote{1120See above.} Even if it were constructed as a dovetail with the slider forming the male half, it would be a cut at a very narrow angle, which would not be enough to guarantee that it could prevent the slider from rising dangerously. However, under the circumstances it is the best interpretation we have available. Another solution would be to reconstruct the trigger mechanism to sit higher on the slider, but this still would not address the problem of the slider struggling to move...
under the disputed component. In any case, the entire ladder assembly would need to be rebuilt in order to make it possible to shoot *Medusa* safely.

The building process for the bolt-shooting catapult, named *Clytaemnestra*, was much more straightforward. Very few problems arose: first, a mistake was made in the design of the hole-carriers, which happened as a result of misreading the text. The hole-carriers had to be completely remade to adjust the positions of the centre stanchions. The second problem arose when the wood used for the new hole-carriers began to split. Because of the position of the cracks which appeared, it was not possible to add a curve to the hole-carriers as recommended by Philon; however, since this part of the design was aesthetic, rather than functional, this was not problematic. Nevertheless, the cracks had to be prevented and the damaged wood had to be protected. Both hole-carriers were therefore banded in metal just as catapults were plated in antiquity, and partly for the same reason.\textsuperscript{1121}

The final problem which arose was concerned with how the case and slider could be attached to the spring-frame. This is something which neither Heron nor Philon discusses, and so Vitruvius was consulted. The chosen solution was to attach narrow blocks above the slider to hold the two parts of the catapult together and to hold the case in the assembly with wedges. However, this had the effect of preventing the slider's movement altogether. The only way to connect the case and slider with the spring-frame which would still allow the slider to move, while allowing the catapult to be dismantled as necessary, was to move the extra blocks down to the level of the top of the case and to trim the sides of the slider to allow it to pass through them.

The final part of this section was concerned with the ammunition for each catapult. To ensure as much consistency as possible, the missiles for the stone-shooting catapult were manufactured from moulded concrete. The bolts for *Clytaemnestra* were made using bolt-heads made by master smith Hector Cole, who followed the construction methods

\textsuperscript{1121}Philon discusses how weakened hole-carriers were supported with iron plates as a last resort. See Philon, *Belopoeica* 57.17-27.
Experimentation

This section began by putting the experiments which would be performed into their historical context. The ancient writers' accounts of the period 350-100BC were searched for references to catapults and their use in sieges and on the field. Factors in the use of artillery which had the potential for experimentation were then extracted from the accounts and collected with suggested methods for testing them. Also noted were generalisations about the use of catapult technology which were common to all or most of the historians' descriptions.

One of the main findings of the first chapter of this section was that the use of catapults as anti-personnel weapons, rather than as a means by which walls could be battered down, far outweighed all other battlefield roles for artillery. Another factor which was common to the occasions on which catapults were used was that there was generally at least one physical barrier between the artillery and the enemy. Catapults were used from siege towers, city walls, earthworks, and river banks, and only rarely were they seen in action on the open battlefield, and even then, troops would be positioned between them and the opposing force. Once in place, it appears that artillery probably was not moved out of position, since none of the historians, even those who seem more interested than the others in catapult technology, ever mentions catapults having their position changed partway through a battle or siege. From the historians' accounts, generals were able to judge where to position their artillery and where to place their forces out of range of the enemy's catapults. Livy is the only one of the historians to give us any evidence for how catapults were transported, and both Arrian and Plutarch give us information about the effects

Sim and Ridge (2011), 84.
Livy, 42.53.4.
catapult bolts could achieve against armour and shields. The psychological effects of facing catapults were also noted by a number of the authors, who suggested that when faced with novel technology, the enemy was liable to flee. Overall, though, the authors seemed fairly uninterested in catapults and their use, though details did filter through to their writings. On the other hand, the infrequency with which artillery appears in the historical narratives could be an indicator that catapults were actually used only infrequently and that they required particular conditions for their effective use.

In the next part of this section, experiments were carried out in order to gain data which could be compared to the historians' accounts. The preliminary testing was mostly qualitative, and aimed to check that the catapults were working safely and to observe where maintenance would be needed during the rest of the testing phase. It was at this point that it was discovered that it was not possible to operate the stone-shooting catapult safely.

The next stage of testing focussed on specific experiments. Range, accuracy, penetration, and the effects of the catapult bolts against armour and a shield were tested. Initial experiments attempted to find the effective range of the bolt-shooter, but problems arose with the level of accuracy which could be achieved. It was found, however, that reasonable accuracy could be achieved at up to 21m, with almost all of the shots taken at this distance landing well within a 1m² archery target. Accuracy was somewhat improved over distance with the development of a shooting technique based upon the relationship between the operator's body position and the case of the catapult. The best range achieved, at 28.95m was much shorter than had originally been anticipated, but was found to be a consistent maximum. The penetration tests showed a remarkable consistency over the distances at which it was possible to conduct this test with the majority of shots penetrating 2.2cm into the plywood target, with one shot which hit at a steeper angle.

1124 Arrian, *Anabasis* 2.27.2 and Plutarch, *Demetrius* 21.3.
1125 See above.
1126 See below.
1127 Plywood was chosen to act as a base material to allow the penetration of the missiles to be measured.
than the others penetrating 3.2cm into the wood. The amount of penetration achieved against armour was significantly lower, with the bolt-heads piercing the metal by 0.65cm. The penetration of the shield was the most dramatic, with the bolt-heads entirely piercing the shield by at least half their length (between 7 and 8cm each time). Two bolt-heads remain stuck in the shield, since they were so solidly fastened in the shield that the shafts of the bolts broke off before the bolt-heads could be pulled free.

Some qualitative results also emerged from this stage of the testing. One of the most important was in the aiming technique used. Initially, the operators aimed by sighting over or through the spring-frame. However, once the catapult was sighted, the operators had to adjust their body positions in order to be able to reach the trigger. This in turn moved the catapult out of position and had a negative effect on the operators' ability to aim. Two observations were made which enabled this problem to be corrected. First, it was noticed that when the catapult was fully torsioned and the slider winched back, the catapult's centre of balance shifted backwards. This meant that a 'sweet spot' appeared, where the catapult held itself balanced at an elevation of 11.64°, which was also very close to the optimum elevation for the ranges at which it was being shot. Having noticed this, it was possible for the operator to adjust the elevation around this 'sweet spot', reducing the amount of error in adjusting the catapult's aim vertically. The problem of how to position the catapult horizontally was solved when it was noticed that bracing the winch against the operator's body helped to stabilise the catapult while it shot. By doing this, an additional benefit was discovered: the operator needed only to look at the target to aim the catapult, without making fine adjustments. It also meant that the operator could use points on their body to reference where the elevation of the catapult needed to be to achieve a certain range (e.g. one operator found that a suitable elevation for one range was at hip height, another found that the same elevation was below that, and a third found that it was at waist height).

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from a consistent starting point.
The final part of this section focused on comparing the information obtained during the testing phase with the ancient writers' accounts. Surprisingly, their accounts proved to be reasonably reliable, with the majority of the points which they made being reflected in the practical tests. The potential for the bolt-shooting catapult to be used as an anti-personnel weapon was established, and the shooting time which was found seemed to agree with the apparent need for a physical barrier between the catapult and the enemy. Difficulties in moving the larger catapult also complemented the implication in the ancient sources that catapults were not moved during battle, though the bolt-shooter proved very simple to reposition. Livy's claim that catapults could be transported in wagons was found to be reasonable, since both catapults retained the ability to be broken down. The ability to estimate range was also found to be justified, as were some of the claims made by the historians about the bolt-shooting catapult's effectiveness against armour and shields.

The ancient historians' accuracy was fairly self-limiting, however. While the descriptions they gave tended, overall, to be reasonably accurate there was little evidence that the historians understood why artillery was used in particular ways. Moreover, most of the historians showed little interest in the use of catapults per se. It seems likely that they felt that artillery did not make for an exciting narrative, whereas the actions and personalities of individual commanders, and the overall scope of wars and battles rather than close observations of the machines used in battle unless they were particularly unusual (e.g. Plutarch's descriptions of the devices invented by Archimedes at the siege of Syracuse) would prove more entertaining and enlightening to their readership.

**Limitations and further research**

The biggest limitation to this work has been the failure of the stone-shooting catapult. The spring-frame itself, where the majority of technical decisions had to be made,
functions well and as expected. The failure of the ladder and slider was an unanticipated problem, and arises from gaps in the text. This problem arose because Philon's technical vocabulary cannot easily be translated at that point. Considerable rebuilding is needed in order to rectify this issue, and this is one area in which further work is needed.

Further limitations exist because of a lack of resources. The ability to test the maximum range of the catapult was significantly reduced by not having an elevated area or platform (or a way in which to raise the catapult up to that level), where experiments could be carried out. Finding such a testing ground would enable the results of this study to be considerably expanded and would improve the research outcomes considerably.

In terms of wider scholarship, this thesis has been hindered by a lack of available research into the properties and construction of sinew and horsehair rope. This means that apart from the qualitative research, much of the testing process has relied on the properties in which nylon rope is similar to sinew cord. As a result, if the limited research which is available is wrong, the outcomes achieved by this study may be less accurate than they would be were more extensive testing of the properties of sinew and horsehair rope carried out and published.

This thesis opens up the possibility for further research in several areas. Continuing with the theme of experimental archaeology, research is needed into how catapults could perform from high positions, to replicate their use on siege towers, platforms, and earthworks. Moreover, once the work on the stone-shooting catapult has been completed, further research is needed into its performance, particularly in terms of its range. However, it would be particularly interesting to test Medusa against different types of walls, since it appears that catapults, on the rare occasions on which they were used directly against city walls, were used to attack both masonry and mudbrick.

This thesis has also highlighted the need for further research into the development of technical writing in the Greek world, since despite the wide scholarship on Roman
technical writing there has been much less focus on the types of manuals and treatises available in the Classical and Hellenistic periods in Greece. The question of the separation of practical writings from theoretical ones is also well worth further consideration, especially in terms of their structures and how their were perceived by their writers and audiences.

This thesis has shown that, despite some problems from gaps in the text, some misreadings, and some difficulties with resources, the approach of using experimental archaeology and text-based research in combination is one which can be applied to the study of military history. More specifically, it can be used to assess the reliability of the ancient historians and to show that much of their knowledge of catapult use in the Hellenistic period was both reasonable and justified. By taking this novel approach, this thesis has contributed an original and replicable methodology to the disciplines of Classics, Ancient History, and Archaeology. Moreover, this thesis has shown where further research is needed in these fields and has attempted to open up further debate into how catapults in the ancient world were constructed, used, and understood.

This thesis has contributed to scholarship on ancient catapult technology and Greek technical writing in several distinct ways. It has proposed an analytical framework which can be used to consider practical technical texts in detail. It has highlighted the fact that Biton's work forms a chiamus and must be considered literary rather than practical, something which has not been considered by scholars to date. It has highlighted problems in the interpretation of Philon's descriptions of the construction of catapults. In particular it has provided solutions for the problematic counter-plate (ὑπόθεμα) in the stone-shooting engine. It has also shown that difficulties of interpretation arise in Philon's explanation of how the slider and ladder connect in the same catapult, which have not been discussed fully until now. Moreover, it has shown through experimentation that the ancient historians
are broadly accurate in their descriptions of catapult use, something which has previously only been taken for granted. This thesis has also shown, by combining text-based research with experimentation, that catapults were a tool for a specific purpose: that they were used primarily for fixed position warfare, especially sieges.
# Philon's Stone-shooting Catapult (10cm Spring Hole)

<table>
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<th>Component</th>
<th>Height</th>
<th>Length</th>
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<th>Thickness</th>
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<td>[V. - suitable]</td>
<td>4.44</td>
<td>5.56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Framework beam joined to table</td>
<td>[V. – 8D]</td>
<td>4.44</td>
<td>5.56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Table</td>
<td>90</td>
<td>17</td>
<td></td>
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</tr>
<tr>
<td>Long joists of table</td>
<td>10</td>
<td>90</td>
<td>2.5</td>
<td></td>
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</tr>
<tr>
<td>Table board</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>Side pole of ladder</td>
<td>1D+</td>
<td>190</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap between side poles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12</td>
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</tr>
<tr>
<td>Ridge-pole</td>
<td>190</td>
<td>2.5</td>
<td>0.56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rungs of ladder</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.67</td>
<td>3.33</td>
</tr>
<tr>
<td>Slider</td>
<td>P. – suitable [V. – 11.5D]</td>
<td>12</td>
<td>2.5</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Winch</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.38</td>
</tr>
<tr>
<td>Arm</td>
<td>60</td>
<td>5</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
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<td>Sing</td>
<td>126</td>
<td></td>
<td></td>
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</tbody>
</table>

All numbers given are cm

P. = Philon
V. = Vitruvius
<table>
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<tr>
<th>Component</th>
<th>Height</th>
<th>Length</th>
<th>Width</th>
<th>Thickness</th>
<th>Breadth</th>
<th>Diameter</th>
</tr>
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<tbody>
<tr>
<td>Spring-hole Frame</td>
<td>41.25</td>
<td>48.75</td>
<td></td>
<td></td>
<td></td>
<td>7.5</td>
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<tr>
<td>Hole-carrier</td>
<td>48.75</td>
<td></td>
<td>11.25</td>
<td>15</td>
<td>7.5</td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11.25</td>
</tr>
<tr>
<td>Side-stanchion</td>
<td>26.25</td>
<td>11.25</td>
<td>4.69</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centre-stanchion</td>
<td>26.25</td>
<td>11.25</td>
<td>2.81</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aperture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.38</td>
</tr>
<tr>
<td>Washer</td>
<td>5.63</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case</td>
<td></td>
<td>120</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side-pieces of case</td>
<td></td>
<td>120</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 2: Illustrations

Previous Reconstructions

Fig. 1: Schramm's *gastraphetes*
Source: Schramm (1980), 16 Abb. 3

Fig. 2: Schramm's Hellenistic stone-shooting catapult
Source: Schramm (1980), 54 Abb. 21
Fig. 3: Schramms’ wedge-engine
Source: Schramm (1980), 59 Abb. 24

Fig. 4: Schramm’s bronze-spring engine
Source: Schramm (1980), 60 Abb. 25
Fig. 5: Schramm's repeat-shooting catapult
Source: Schramm (1980), 61 Abb. 27

Fig. 6: Schramm's pneumatic catapult
Source: Schramm (1980), 63 Abb. 28
Fig. 7: Ermine Street Guard *catapulta* front view

Fig. 8: Ermine Street Guard *catapulta* close-up of steel plating

Fig. 9: Ermine Street Guard *catapulta* close-up of bowstring
Fig. 10: Ermine Street Guard *catapulta* in operation

Fig. 11: Ermine Street Guard Xanten replica
   front view

Fig. 12: Ermine Street Guard Xanten replica
   rear view
Ancient and Medieval Evidence

Ancient

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Source: Marsden (1969), Plate 3

Fig. 14: The Cupid Gem (magnified c.6:1)
Source: Marsden (1969), Plate 2
Fig. 15: Illustration of *gastraphetes* (Codex P fol. 72v)
Source: Diels and Schramm (1970), 9 Bild 3

Fig. 16: Illustration of the *gastraphetes* table? (Codex P fol. 74v)
Source: Diels and Schramm (1970), 23 Bild 9
Fig. 17: Illustration of palintone engine? (Codex P fol. 74)
Source: Diels and Schramm (1970), 27 Bild 12

Fig. 18: Illustration of palintone engine? (Codex P fol. 76v)
Source: Schramm (1980), 13 Abb. 2
Fig. 19: Illustration of *gastraphetes* (Codex M fol. 47v)
Source: Diels and Schramm (1970), 11 Bild 5

Fig. 20: Illustration of *gastraphetes* and table (Codex M fol. 49v)
Source: Diels and Schramm (1970), 23 Bild 8
Fig. 21: Unclear illustration from M, possibly *euthytone* engine or *gastraphetes* (Codex M. foll. 49)
Source: Diels and Schramm (1970), 26 Bild 11

Fig. 22: Illustration of *euthytone* engine (Codex M fol. 52v)
Source: Diels and Schramm (1970), 41 Bild 19
Fig. 23: Illustration of stretcher for torsion engines (Codex M fol. 54)
Source: Diels and Schramm (1970), 45 Bild 21

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Source: Commare (1999a), 60 fig. 14
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Fig. 60: Stand under construction

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Fig. 69: First stage of range testing against plywood board

Fig. 70: Second stage of range testing on open ground with the author and Esdi Hughes

Photo credit: John Hughes
Fig. 71: Best grouping in open field testing
(furthest shot to 94ft, grouping width 10ft)
Photo credit: John Hughes

Fig. 72: Accuracy testing with 1m² archery target (group shot by Esdi Hughes)

Fig. 73: Accuracy testing with 1m² archery target (group shot by the author)
Fig. 74: Improved aiming method based on body position
(with Esdi Hughes)

Fig. 75: Improved aiming method based on body position
(with Esdi Hughes)

Photo credit: John Hughes
Fig. 76: Testing against armour

Fig. 77: Level of penetration of armour

Fig. 78: Angle of strike against armour
Fig. 79: Level of penetration of armour

Fig. 80: Damage done to armour

Fig. 81: Damage done to armour
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Fig. 83: Penetration of shield (front view)

Fig. 84: Penetration of shield (rear view)
Fig. 85: Bolt-head caught in shield handle

Fig. 86: Hits to shield (with the author)
Photo credit: Esdi Hughes
Structure of the Catapults

Medusa

Fig. 87: Line drawing of Philon's stone-shooting catapult

a) Annotated by author, with changes made in Medusa highlighted
b) Not annotated

Source: Marsden (1969), 35 fig. 17
Fig. 88: Structure of the stone-thrower's spring-frame
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Fig. 90: Line drawing of Philon's bolt-shooting catapult
a) Annotated by author, with changes made in Clytaemnestra highlighted
Source: Marsden (1969), 34 fig. 16
Fig. 90: Line drawing of Philon's bolt-shooting catapult

b) Not annotated

Source: Marsden (1969), 34 fig. 16
Fig. 91: Structure of the bolt-shooter (front view)
Fig. 92: Structure of the bolt-shooter (side/rear view)
Fig. 93: Operator's view of bolt-shooter
## Appendix 3: Glossary

### Table 12: General Glossary

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catapult, non-torsion</td>
<td>Catapult which is powered by tension, usually a composite bow. This is probably the earliest form of artillery, likely to have been invented circa 399BC. The type of catapult in this category is the <em>gastraphetes</em> (ὁ γαστραφέτης), also known as the 'belly-bow'. Such catapults could use bolts or stones as missiles. Our best sources for this type of catapult are Heron and Biton. See also illustrations.</td>
</tr>
<tr>
<td>Catapult, torsion</td>
<td>Catapult which is powered by twisted rope. This type of artillery seems to have emerged around the middle of the fourth century BC, and in the period considered by this thesis was of the two-armed type. These catapults could use either bolts or stones as missiles; the bolt-throwing type is known as the <em>oxybeles</em> (ὁ ὀξυβελής), and the stone-throwing type is known as the <em>lithobolus</em> (ὁ λιθόβολος) or the <em>petrobolus</em> (ὁ πετροβόλος). They are also known as <em>euhtyton</em> (ὁ εὐθύτονος) or <em>palintono</em> (ὁ παλίντονος) engines respectively because of the shape of their spring-frames. Our best sources for torsion catapults are Philon and Heron. See also illustrations.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Term</th>
<th>See</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euthytone</td>
<td>See <strong>Catapult, torsion.</strong></td>
</tr>
<tr>
<td>Gastraphetes</td>
<td>See <strong>Catapult, non-torsion.</strong></td>
</tr>
<tr>
<td>Helopolis</td>
<td>Literally 'city-taker': a large, multi-storey siege tower. An example is described by Biton (<em>Construction of War Machines</em> 52.1-56.7).</td>
</tr>
<tr>
<td>Lithobolus</td>
<td>See <strong>Catapult, torsion.</strong></td>
</tr>
<tr>
<td>Oxybeles</td>
<td>See <strong>Catapult, torsion.</strong></td>
</tr>
<tr>
<td>Palintono</td>
<td>See <strong>Catapult, torsion.</strong></td>
</tr>
<tr>
<td>Petrobolus</td>
<td>See <strong>Catapult, torsion.</strong></td>
</tr>
</tbody>
</table>
Table 13: Catapult Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arms</td>
<td>b</td>
<td>Both of these fit into the Spring-rope and are joined by the bowstring. Their movement when the Trigger is released forces the missile forward and through the Spring-frame, in the desired direction. In both types of catapult in this period, the Arms are straight; by the mid-second century BC, the arms in the bolt-throwing catapult had developed a curved shape.</td>
</tr>
<tr>
<td>Base</td>
<td>b</td>
<td>This is the stand on which the catapults rest.</td>
</tr>
<tr>
<td>Block</td>
<td>e</td>
<td>This is a section fastened to the back of the Slider to which the Winch is attached by a rope. This allows the Slider to be retracted using the winch.</td>
</tr>
<tr>
<td>Bolt</td>
<td>e</td>
<td>This is the missile propelled by the Euthytone engine. A Bolt is constructed in a similar way to an arrow, but is considerably larger and thicker. Its head is also much larger and thicker than on a conventional arrow.</td>
</tr>
<tr>
<td>Case</td>
<td>e</td>
<td>This is the component which contains the channel or groove in which the Slider runs. The channel is shaped like a dovetail, to hold the Slider in position safely. In the stone-throwing catapult, this component is replaced with the Ladder.</td>
</tr>
<tr>
<td>Claw</td>
<td>b</td>
<td>This is part of the Trigger mechanism. Supported by the trigger bar, it holds the bowstring down while the Slider is winched back into position. When the trigger bar is removed, the Claw is forced up and backwards by its own weight, releasing the bowstring and with it the missile.</td>
</tr>
<tr>
<td>Counter-plate</td>
<td>p</td>
<td>Plate fitted under the Hole-carrier for extra strength in Philon, or a second Washer to prevent the main one from digging into the Spring-frame in Heron.</td>
</tr>
<tr>
<td>Hole-carriers</td>
<td>b</td>
<td>These are the two horizontal beams which make up the top and bottom of the Spring-frame. In the bolt-throwing catapult, these are fairly simple beams made from a single piece of wood; in the stone-throwing catapult, they are rhomboidal and constructed from two or more pieces of wood. See also illustrations.</td>
</tr>
<tr>
<td>Ladder</td>
<td>p</td>
<td>This performs the same function as the Case in the bolt-throwing catapult. In the stone-throwing catapult, the channel is rectangular in cross section unlike the dovetail of the Case in the bolt-throwing catapult.</td>
</tr>
<tr>
<td>Rest</td>
<td>e</td>
<td>Prop at the back of the Base, which rests on the Stay; helps to hold the bolt-throwing catapult in position while the missile is loaded.</td>
</tr>
<tr>
<td>Rope</td>
<td>b</td>
<td>See Spring-rope.</td>
</tr>
<tr>
<td>Slider</td>
<td>b</td>
<td>Moveable component onto which the missile is placed before it is shot; it protrudes from the front of the Spring-frame before being winched back to increase the power.</td>
</tr>
<tr>
<td>Term</td>
<td>Type</td>
<td>Description</td>
</tr>
<tr>
<td>----------------------</td>
<td>------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Sling</td>
<td>p</td>
<td>The missile in the stone-throwing catapult sits in this; it is attached to the bowstring.</td>
</tr>
<tr>
<td>Spring-frame</td>
<td>b</td>
<td>Made up of the <strong>Hole-carriers</strong> and the <strong>Stanchions</strong>. The <strong>Spring-ropes</strong> run through the <strong>Spring-holes</strong> in the <strong>Hole-carriers</strong> and between the <strong>Side</strong> and <strong>Centre Stanchions</strong>. The <strong>Washers</strong> sit above the <strong>Spring-holes</strong>. The wooden parts when assembled together comprise the <strong>Spring-frame</strong>.</td>
</tr>
<tr>
<td>Spring-hole</td>
<td>b</td>
<td>This is the hole through which the <strong>Spring-rope</strong> passes; the diameter of this hole is the key measurement for all other components of the catapult. In a stone throwing catapult, this is measurement is $\frac{1}{10}$ multiplied by the cube root of the weight of the missile (in drachmae); in a bolt-throwing catapult, the measurement is one ninth of the length of the missile.</td>
</tr>
<tr>
<td>Spring-rope</td>
<td>b</td>
<td>The <strong>Spring-rope</strong> is constructed from thin rope or thick cord. Sinew was the preferred material, though horsehair or human hair could be substituted. For more details on its construction, see above in the main body of the thesis under 'Ropes'. The <strong>Spring-rope</strong>, when twisted, supplies the power to the catapult. There are two rope-springs in each <strong>Spring-frame</strong>. The <strong>Spring-ropes</strong> run through the <strong>Spring-holes</strong> in the <strong>Hole-carriers</strong>, between the <strong>Side</strong> and <strong>Centre Stanchions</strong>, and through the <strong>Washers</strong>. The tightening of the <strong>Washers</strong> creates torsion power.</td>
</tr>
<tr>
<td>Stanchions, Side</td>
<td>b</td>
<td>These are fixed to the <strong>Hole-carriers</strong> by <strong>Tenons</strong> and are the outer uprights of the <strong>Spring-frame</strong>.</td>
</tr>
<tr>
<td>Stanchions, Centre</td>
<td>b</td>
<td>These are fixed to the <strong>Hole-carriers</strong> by <strong>Tenons</strong> and are the inner uprights of the <strong>Spring-frame</strong>. The <strong>Case</strong> or <strong>Ladder</strong> and <strong>Slider</strong> sit between them; the missile is projected between them.</td>
</tr>
<tr>
<td>Stay</td>
<td>e</td>
<td>Leg at the back of the <strong>Base</strong>, joined to it by the <strong>Stop</strong>. The <strong>Rest</strong> rests on it to help to hold the bolt-throwing catapult in position while the missile is loaded.</td>
</tr>
<tr>
<td>Stop</td>
<td>e</td>
<td>Joins the <strong>Stay</strong> to the column in the <strong>Base</strong>.</td>
</tr>
<tr>
<td>Table</td>
<td>p</td>
<td>Joins the <strong>Hole-carriers</strong> in the stone-throwing catapult together.</td>
</tr>
<tr>
<td>Tenons</td>
<td>b</td>
<td>Pegs made up as part of other components (especially in the <strong>Stanchions</strong> and <strong>Base</strong>) which fit into holes in other components (especially the <strong>Hole-carriers</strong>) to join them together.</td>
</tr>
<tr>
<td>Trigger</td>
<td>b</td>
<td>Made up of the <strong>Claw</strong> and the trigger bar, and attached to the <strong>Block</strong>. The movement of the trigger bar from under the...</td>
</tr>
</tbody>
</table>
Claw raises the Claw which releases the bowstring.

**Washer**  b  Metal cylindrical ring with a bar passed through the top. The spring-rope is passed through the washer and over the bar, and the washer and rope are twisted to provide the torsion force. Holes drilled in the flange which surrounds the washer match with identical holes in a flat washer below (see **Counter-plate**); pegs placed through these holes hold the washer and rope in position. See also **Spring-rope** and **Spring-frame**.

**Winch**  b  Simple **Winch** mechanism, attached to the **Slider** by the **Block**; used to retract the **Slider** and hold it in place while the missile is released.

N.B. See Illustrations for diagrams of the catapult components.

Key:

p = component used in palintone engine (stone-throwing catapult)

e = component used in euthytone engine (bolt-throwing catapult)

b = used in both engines

**Bold** = cross-reference
Table 14: Greek Glossary

NB: where the Greek vocabulary is confusing or still debated, multiple sources have been used to provide a gloss. The *LSJ* has been used where appropriate, but often misunderstands the technical terminology related to catapult technology.\textsuperscript{1128} Therefore, the glosses given which do not reference the *LSJ* or any other author are my own, and are based on contextual evidence from within the texts.

<table>
<thead>
<tr>
<th>Greek</th>
<th>English</th>
</tr>
</thead>
<tbody>
<tr>
<td>ἀγκύλη</td>
<td>loop</td>
</tr>
<tr>
<td>ἀγκών</td>
<td>'arm' (word has emphasis on the fact that the shape is bent – <em>LSJ</em>)</td>
</tr>
<tr>
<td>ἀνάλογος</td>
<td>proportion, proportional</td>
</tr>
<tr>
<td>ἀναπαυστήριος</td>
<td>prop, rest</td>
</tr>
<tr>
<td>ἀντηρίδιον</td>
<td>stanchion, support, base – <em>LSJ</em>; 'stay' - Marsden</td>
</tr>
<tr>
<td>ἀντηρίς</td>
<td>strut</td>
</tr>
<tr>
<td>ἀντιστάτης</td>
<td>'counter-stanchion' – inner upright in the spring-frame (<em>palintone</em>)</td>
</tr>
<tr>
<td>ἀξίωνια</td>
<td>bars, axles (context dependant)</td>
</tr>
<tr>
<td>ἀποσφην</td>
<td>wedge tight</td>
</tr>
<tr>
<td>ἀριθμός</td>
<td>number</td>
</tr>
<tr>
<td>αὔξη</td>
<td>dimension</td>
</tr>
<tr>
<td>ἁφαιρετός</td>
<td>separable</td>
</tr>
<tr>
<td>βάσις</td>
<td>pedestal, base</td>
</tr>
<tr>
<td>γαστραφτής</td>
<td>belly-bow, <em>gastraphetes</em> (non-torsion, crossbow catapult)</td>
</tr>
<tr>
<td>δάκτυλος</td>
<td>'finger', the bar part of the trigger mechanism</td>
</tr>
<tr>
<td>διάπηγμα</td>
<td>crossbar</td>
</tr>
<tr>
<td>διπλάσιος</td>
<td>double</td>
</tr>
<tr>
<td>διτόρμος</td>
<td>double tenon</td>
</tr>
<tr>
<td>διτροχία</td>
<td>windlass (specifically with two wheels)</td>
</tr>
<tr>
<td>δίχηλος</td>
<td>double prong</td>
</tr>
<tr>
<td>δίωστρα</td>
<td>'slider'</td>
</tr>
<tr>
<td>δόμος</td>
<td>ply, strand (part of the rope construction)</td>
</tr>
<tr>
<td>ἔδαφος</td>
<td>floor</td>
</tr>
<tr>
<td>ἐκκοπή</td>
<td>notch, a cutting out</td>
</tr>
<tr>
<td>ἔντόνιον</td>
<td>'stretcher' – for stretching the spring-rope</td>
</tr>
<tr>
<td>ἔντορνια</td>
<td>raised rim</td>
</tr>
<tr>
<td>ἐπειλέω</td>
<td>wind up (a machine)</td>
</tr>
</tbody>
</table>

---
\textsuperscript{1128}E.g. σῦργες, which the *LSJ* defines as the 'groove or barrel of a catapult', which actually refers to the case (which cannot be accurately described as a 'groove or barrel').
<table>
<thead>
<tr>
<th>Greek Word</th>
<th>English Translation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ἐπιζυγίς</td>
<td>'lever' (bar used to create the torsion in the spring)</td>
</tr>
<tr>
<td>ἐπιστροφή</td>
<td>twisting</td>
</tr>
<tr>
<td>ἐπιτοξίτις</td>
<td>'groove'</td>
</tr>
<tr>
<td>ἐπιφάνεια</td>
<td>the visible surface</td>
</tr>
<tr>
<td>εὐλυτος</td>
<td>easy to dismantle/untie</td>
</tr>
<tr>
<td>εὐτονος</td>
<td>sinewy, strong</td>
</tr>
<tr>
<td>θεώρημα</td>
<td>scheme, plan</td>
</tr>
<tr>
<td>κανόν</td>
<td>beam</td>
</tr>
<tr>
<td>κανόνιον</td>
<td>bar</td>
</tr>
<tr>
<td>καρχήσιον</td>
<td>'cage or chamber in a torsion-engine' LSJ – 'universal joint' Marsden and DeVoto</td>
</tr>
<tr>
<td>καταγωγή</td>
<td>withdrawal rest, pull-back rest</td>
</tr>
<tr>
<td>κατακλείεις</td>
<td>pawl – part of the ratchet system, the bar which drops down; bracket, cap (in Biton)</td>
</tr>
<tr>
<td>κάτοχος</td>
<td>holders, stanchions – part of trigger mechanism</td>
</tr>
<tr>
<td>κέστρα</td>
<td>hammer, bolt hammered in to pack the spring-ropes in</td>
</tr>
<tr>
<td>κιλλίβας</td>
<td>three-legged stand – LSJ; trestle – Marsden</td>
</tr>
<tr>
<td>κίον</td>
<td>pillar</td>
</tr>
<tr>
<td>κλιμακίς</td>
<td>ladder = the case, but in palintonic engines</td>
</tr>
<tr>
<td>κοίλασμα</td>
<td>groove</td>
</tr>
<tr>
<td>κοίλος</td>
<td>hollow, concave</td>
</tr>
<tr>
<td>κόραξ</td>
<td>hook, pawl</td>
</tr>
<tr>
<td>κρατήρ</td>
<td>'cup-bracket' – Marsden</td>
</tr>
<tr>
<td>κτηδόνες ξύλου</td>
<td>'grain of wood' – LSJ</td>
</tr>
<tr>
<td>κυρτός</td>
<td>curved, convex</td>
</tr>
<tr>
<td>κόλον</td>
<td>limb, arm (in Heron, coil, section of rope)</td>
</tr>
<tr>
<td>λείος</td>
<td>smooth</td>
</tr>
<tr>
<td>λεπίς</td>
<td>scale, plate</td>
</tr>
<tr>
<td>λογοθεσία</td>
<td>accounts, description; 'list of dimensions' – Marsden</td>
</tr>
<tr>
<td>μάγγανον</td>
<td>'block' of a pulley – LSJ; context suggests 'end'</td>
</tr>
<tr>
<td>μέρος</td>
<td>part (i.e. 'share, portion' – LSJ)</td>
</tr>
<tr>
<td>μεσοστάτης</td>
<td>centre-stanchion – inner upright in the spring-frame (eurythone)</td>
</tr>
<tr>
<td>μήκος</td>
<td>length</td>
</tr>
<tr>
<td>μήρωμα</td>
<td>thread, strand – sense of the word is in 'drawing out'</td>
</tr>
<tr>
<td>μογλός</td>
<td>crowbar</td>
</tr>
<tr>
<td>νευρή</td>
<td>bowstring, rope in the torsion frame</td>
</tr>
<tr>
<td>νεῦρον</td>
<td>sinew, tendon</td>
</tr>
<tr>
<td>ὅμαλός</td>
<td>smooth</td>
</tr>
<tr>
<td>Ancient Greek</td>
<td>English</td>
</tr>
<tr>
<td>--------------</td>
<td>---------</td>
</tr>
<tr>
<td>ὀνίσκος</td>
<td>windlass</td>
</tr>
<tr>
<td>ὀπή</td>
<td>hole, aperture</td>
</tr>
<tr>
<td>ὀρθογώνιον</td>
<td>rectangle</td>
</tr>
<tr>
<td>ὀρθός</td>
<td>upright, at right angles to</td>
</tr>
<tr>
<td>παραλληλόγραμμος</td>
<td>bounded by parallel lines</td>
</tr>
<tr>
<td>παραστάτης</td>
<td>side-stanchion – outer upright on the spring-frame</td>
</tr>
<tr>
<td>πάχος</td>
<td>thickness</td>
</tr>
<tr>
<td>πελεκτίνος</td>
<td>dovetail (as in 'dovetail joint' in woodwork)</td>
</tr>
<tr>
<td>περιστομίς</td>
<td>clip, spanner, calliper used for measuring the thickness of the spring-rope</td>
</tr>
<tr>
<td>περίτρητον</td>
<td>hole-carrier – horizontal beam in spring-frame, containing the spring-holes</td>
</tr>
<tr>
<td>περιφέρεια</td>
<td>rounded surface, circumference</td>
</tr>
<tr>
<td>περόνη</td>
<td>pin</td>
</tr>
<tr>
<td>πῆγμα</td>
<td>framework</td>
</tr>
<tr>
<td>πλάγιος</td>
<td>crooked, diagonal – can also mean sides</td>
</tr>
<tr>
<td>πλάτη</td>
<td>breadth, width</td>
</tr>
<tr>
<td>πλάτος</td>
<td>breadth, width</td>
</tr>
<tr>
<td>πλέκω</td>
<td>plait, twist</td>
</tr>
<tr>
<td>πλινθίον</td>
<td>frame, spring-frame</td>
</tr>
<tr>
<td>πολύσπαστος</td>
<td>compound-pulley</td>
</tr>
<tr>
<td>πτέρυξ</td>
<td>'protector' – Marsden; 'front frame' – LSJ; 'wing' – DeVoto – assembled palintone engine</td>
</tr>
<tr>
<td>πτηνός</td>
<td>'flying, winged' – LSJ; in this context 'heel'</td>
</tr>
<tr>
<td>ῥαφίς</td>
<td>needle</td>
</tr>
<tr>
<td>σανίς</td>
<td>board, plank</td>
</tr>
<tr>
<td>σκαστηρία</td>
<td>trigger</td>
</tr>
<tr>
<td>σκέλη</td>
<td>side-piece</td>
</tr>
<tr>
<td>σκοπός</td>
<td>mark, target</td>
</tr>
<tr>
<td>σκυτάλη</td>
<td>handle, hand-spike</td>
</tr>
<tr>
<td>στήμα</td>
<td>shaft (stanchion)</td>
</tr>
<tr>
<td>στήμων</td>
<td>thread</td>
</tr>
<tr>
<td>στρογγύλλος</td>
<td>round</td>
</tr>
<tr>
<td>στροφεύς</td>
<td>hinge</td>
</tr>
<tr>
<td>στυλίσκος</td>
<td>stanchion, small column</td>
</tr>
<tr>
<td>συμφύς</td>
<td>attached</td>
</tr>
<tr>
<td>συνίστημι</td>
<td>calculate</td>
</tr>
<tr>
<td>σύριγξ</td>
<td>case – literally, tube</td>
</tr>
<tr>
<td>Greek Word</td>
<td>English Translation</td>
</tr>
<tr>
<td>------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>σφενδόνη</td>
<td>sling</td>
</tr>
<tr>
<td>σφήν</td>
<td>wedge</td>
</tr>
<tr>
<td>σφύρα</td>
<td>hammer</td>
</tr>
<tr>
<td>σχαστηρία</td>
<td>trigger</td>
</tr>
<tr>
<td>σχήμα</td>
<td>shape, form</td>
</tr>
<tr>
<td>σωλήν</td>
<td>groove, channel</td>
</tr>
<tr>
<td>τάσις</td>
<td>stretching</td>
</tr>
<tr>
<td>τετράγωνος</td>
<td>square</td>
</tr>
<tr>
<td>τοῖχος</td>
<td>wall, side</td>
</tr>
<tr>
<td>τόνων</td>
<td>spring, rope spring in the torsion frame; can also mean 'brace' (e.g. in Biton 49.10)</td>
</tr>
<tr>
<td>τόπος</td>
<td>place, space, area, position</td>
</tr>
<tr>
<td>τόρμος</td>
<td>tenon (hole into which a peg is stuck, type of wood joint)</td>
</tr>
<tr>
<td>τράπεζα</td>
<td>table</td>
</tr>
<tr>
<td>τρήμα</td>
<td>hole, perforation, aperture</td>
</tr>
<tr>
<td>τριβεύς</td>
<td>flange – raised rim on the washer</td>
</tr>
<tr>
<td>τροχιά</td>
<td>strand in the spring-cord construction</td>
</tr>
<tr>
<td>τροχίλος</td>
<td>sheave – wheel in a pulley system</td>
</tr>
<tr>
<td>τρύπημα</td>
<td>hole</td>
</tr>
<tr>
<td>ύπογράφῳ</td>
<td>sketch</td>
</tr>
<tr>
<td>ύπόθεμα</td>
<td>'base' – LSJ; 'counter-plate' – Marsden; 'underpiece' – DeVoto; Heron/Ctesibius and Philon use this term to mean different components.</td>
</tr>
<tr>
<td>ύποπτερνίς</td>
<td>'knob' – LSJ; 'heel-pad' – Marsden, deVoto – the part on which the arms rest in the torsion-engine</td>
</tr>
<tr>
<td>άγιος</td>
<td>height</td>
</tr>
<tr>
<td>χείρ</td>
<td>claw in the trigger mechanism</td>
</tr>
<tr>
<td>χελωνάριον</td>
<td>'tail-piece' of the stand of a torsion-engine – LSJ; according to context, 'block' at the back of the slider</td>
</tr>
<tr>
<td>χελώνιον</td>
<td>'knob' – LSJ; 'pad' – Marsden, DeVoto - on which the arms rest in the torsion-engine</td>
</tr>
<tr>
<td>χιλή</td>
<td>notch of an arrow, also prong in the claw</td>
</tr>
<tr>
<td>χοινικίς</td>
<td>washer (metal ring which holds spring and crosspiece)</td>
</tr>
</tbody>
</table>
Table 15: Ancient and Modern Measurements

a) Lengths

<table>
<thead>
<tr>
<th></th>
<th>mm</th>
<th>in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 dactyl</td>
<td>19.3</td>
<td>0.76</td>
</tr>
<tr>
<td>1 palm (= 4 dactyls)</td>
<td>77.1</td>
<td>3.04</td>
</tr>
<tr>
<td>1 span (= 12 dactyls)</td>
<td>231.2</td>
<td>9.12</td>
</tr>
<tr>
<td>1 foot (= 16 dactyls)</td>
<td>308.3</td>
<td>12.16</td>
</tr>
<tr>
<td>1 cubit (= 24 dactyls)</td>
<td>462.4</td>
<td>18.21</td>
</tr>
</tbody>
</table>

Measurements of length could and did vary from city to city – the measurement of 1 foot ranged from 27-35cm (270-350mm). Marsden here takes the middle ground.

b) Weights

<table>
<thead>
<tr>
<th></th>
<th>g</th>
<th>lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mina</td>
<td>436</td>
<td>0.96</td>
</tr>
<tr>
<td>5 minae</td>
<td>2180</td>
<td>4.81</td>
</tr>
<tr>
<td>10 minae</td>
<td>4360</td>
<td>9.61</td>
</tr>
<tr>
<td>15 minae</td>
<td>6540</td>
<td>14.42</td>
</tr>
<tr>
<td>20 minae</td>
<td>8720</td>
<td>19.22</td>
</tr>
<tr>
<td>30 minae</td>
<td>13080</td>
<td>28.84</td>
</tr>
<tr>
<td>50 minae</td>
<td>21800</td>
<td>48.06</td>
</tr>
<tr>
<td>1 talent (= 60 minae)</td>
<td>26160</td>
<td>57.67</td>
</tr>
<tr>
<td>2.5 talents (= 150 minae)</td>
<td>65400</td>
<td>144.18</td>
</tr>
<tr>
<td>3 talents (= 180 minae)</td>
<td>78480</td>
<td>173.02</td>
</tr>
</tbody>
</table>

1129 These figures are taken directly from Marsden (1969), xix.
1130Dilke (1987), 26
1131The ancient figures (apart from 1 mina and 5 minae) are taken from the list of stone-thrower sizes given by Philon – Philon, Belopoeica 51.18-27. The weights are taken from Dilke (1987), 47 and represent the Attic and Euboean standards. Evidence from Rhodes suggests that these were the standard weights used in catapult-shot – see Marsden (1999), xviii. Note also that Marsden's figure for 1 mina is slightly higher, at 436.6g – see Marsden (1999), xviii.
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