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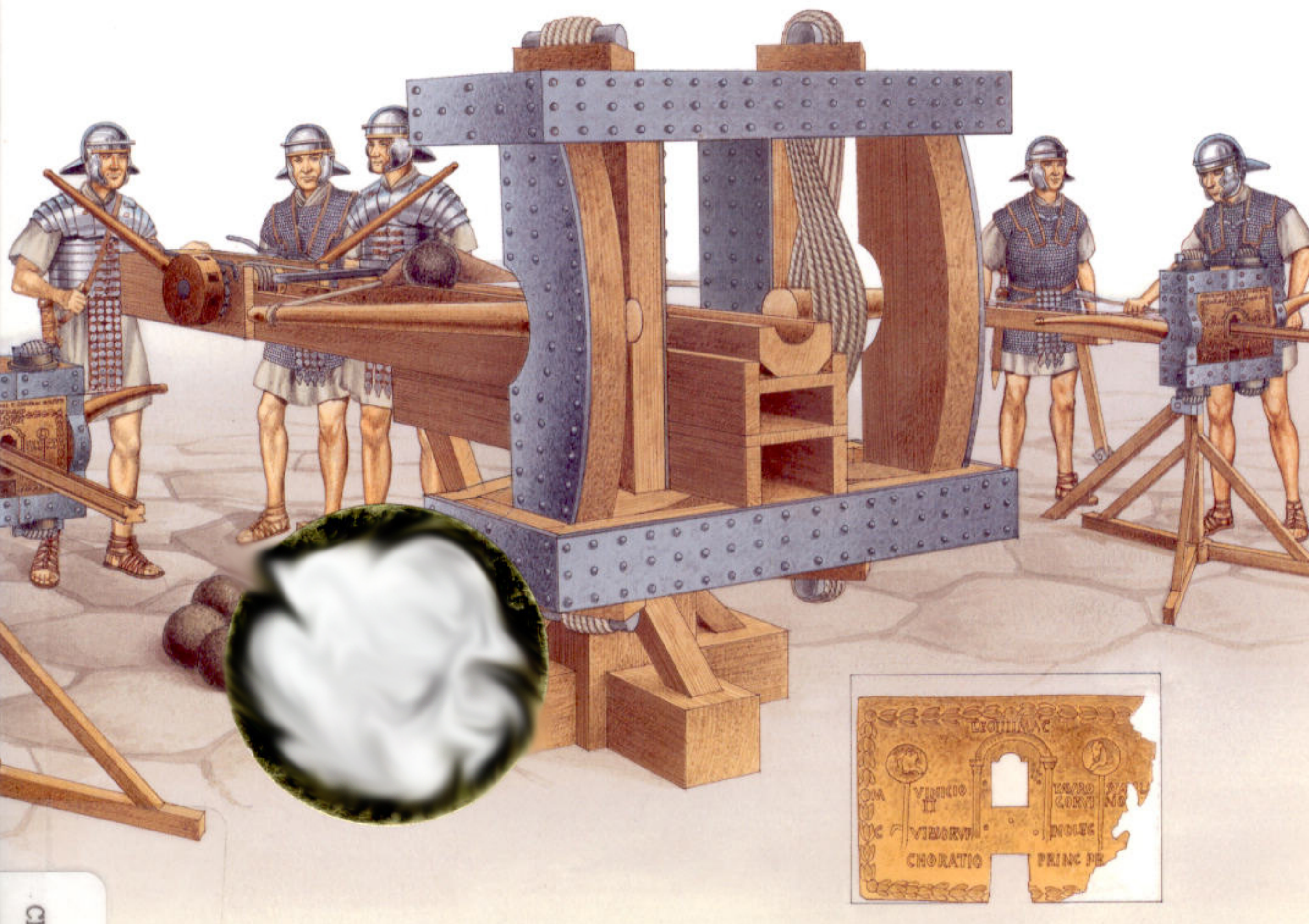
Greek and Roman Artillery 399 BC–AD 363



Duncan B Campbell • Illustrated by Brian Delf

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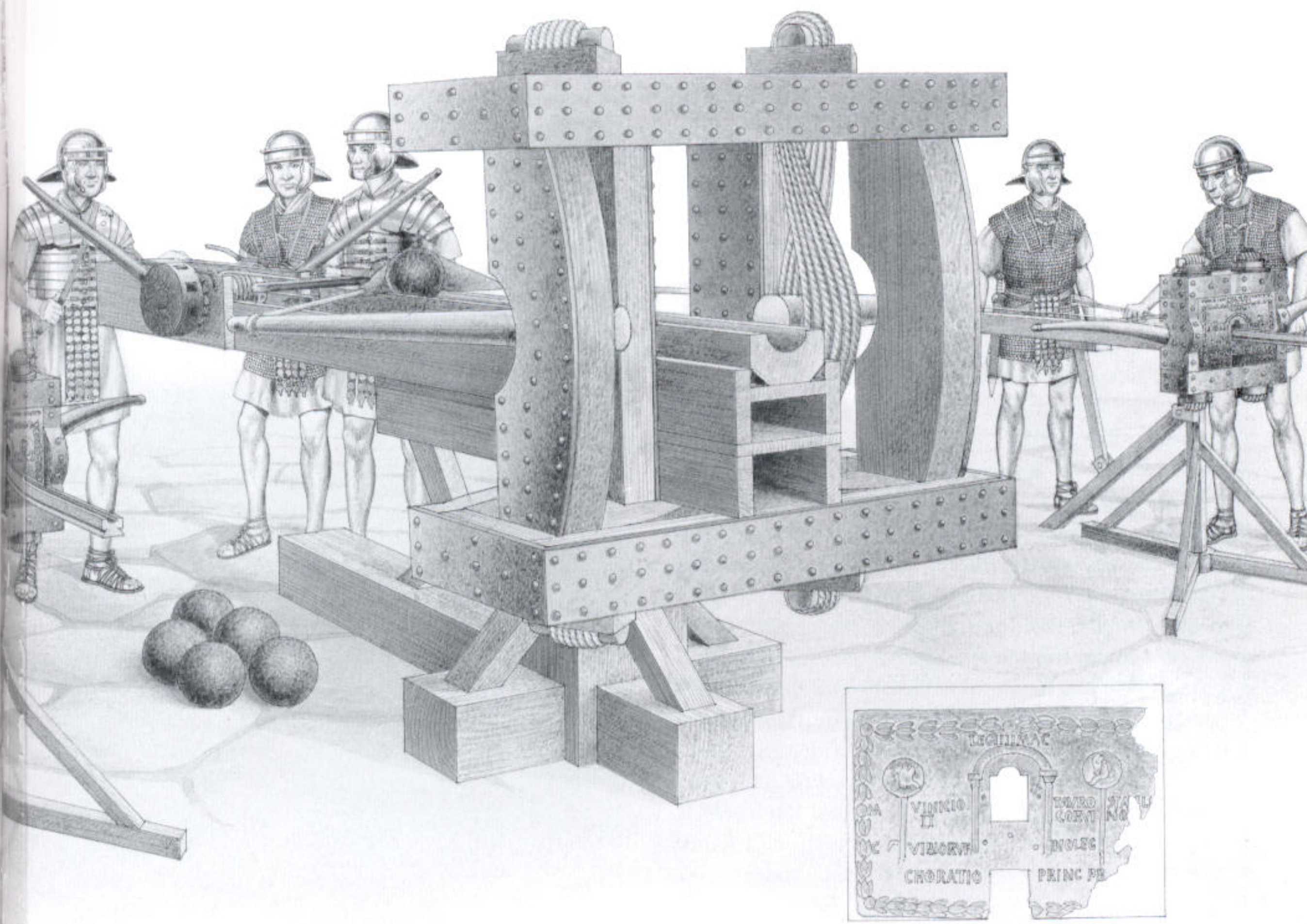

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A note on measurements

Although the Romans imposed a standard system of weights and measures across their empire, several different systems had existed in the Greek world. For example, the Greek foot, subdivided into 16 daktyls, has been found to vary between 27 and 35cm, depending upon the geographical region. However, an intermediate value of 30.83cm was widely employed, and may be deemed an acceptable average. The standard foot of the Romans, by contrast, measured 29.57cm; it was similarly subdivided into 16ths (called digits, the Latin form of the Greek daktyls), or into 12ths.

Several weight standards were employed in the Greek world, all based on the 60-mina talent. However, the Attic standard used at Athens, with its mina of 436.6g, was pre-eminent. The Roman system was based on the pound (*libra*) of 327.45g, which was exactly three-quarters of the Attic mina.

Greek weights and measurements:
60 minas = 1 talent = 26.2kg
24 daktyls = 2 spans = 1 cubit = 46.24cm
16 daktyls = 1ft = 30.83cm

Roman weights and measurements:
80 *librae* = 1 talent = 26.2kg
24 digits = 2 spans = 1 cubit = 44.35cm
16 digits = 12in. = 1ft = 29.57cm

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I am pleased to acknowledge the generosity of several individuals in supplying illustrations for this book: Dietwulf Baatz; Megan Doyon (Yale University Art Gallery); Chris Haines (Ermine Street Guard); J. D. Vicente Redón; and Alan Wilkins. I owe a greater debt to Prof. Dr Baatz, who has patiently answered my queries over the last 20 years and whose publication of the Hatra *ballista* first stirred my interest in ancient artillery. For this reason, I respectfully dedicate this book to him. Finally, it would be remiss of me not to thank Brian Delf and my editor, Marcus Cowper, for their patience in converting my notes and sketches into a fine series of colour plates.

GREEK AND ROMAN ARTILLERY 399 BC–AD 363

INTRODUCTION

The invention of the catapult

The historian Diodorus Siculus writes that, in 399 BC, the catapult (*katapeltikon*) was invented under the patronage of Dionysius I, tyrant of Syracuse. However, the weapon did not suddenly arrive out of the blue. In a work entitled *Ctesibius's manufacture of missile weapons* (*Ktēsibiou Belopoiika*), the Roman engineer Heron of Alexandria explains that the catapult was inspired by an earlier mechanical weapon, the 'belly shooter' (*gastraphetēs*). Another author, Biton, who is often unjustly discredited as a fraud, describes two advanced forms of the *gastraphetēs*; he credits these to Zopyrus, an engineer from Tarentum in southern Italy who may have been active towards the end of the 5th century BC. Developments made by Zopyrus brought this mechanical hand-weapon into the realm of crewed artillery and allowed the development of the catapult.

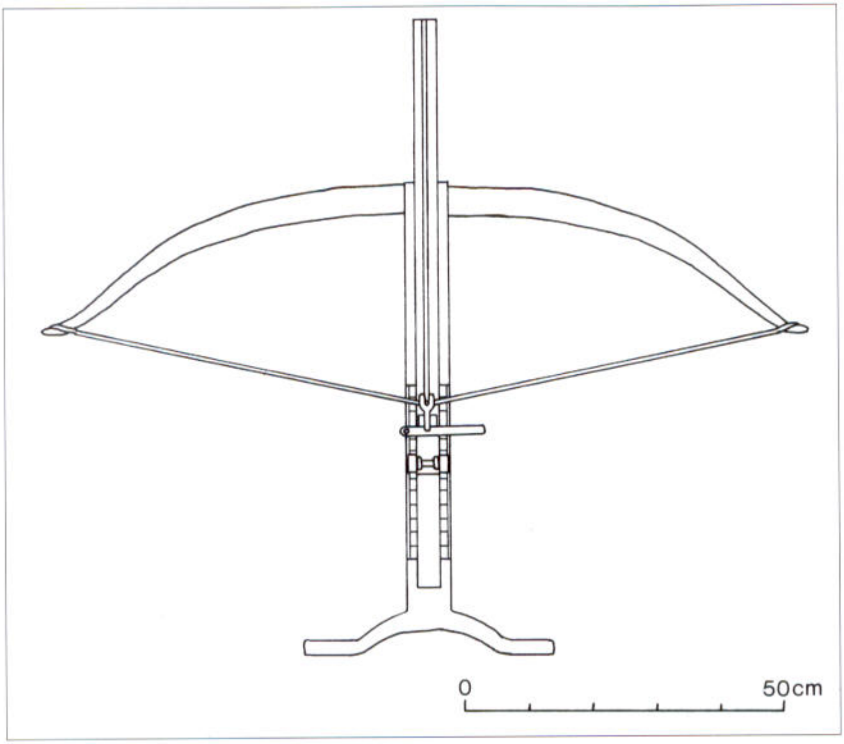
Schramm's reconstruction of the *gastraphetēs* incorporated a steel bow, which is now considered to be wrong. The manufacture of an authentic composite bow of this size was a highly specialised business that might have taken up to a year to complete. (Author's photo)

The *gastraphetēs*

In its original form, the *gastraphetēs* consisted of a powerful composite bow, mounted transversely on a stock so that it vaguely resembled the later crossbow. It took its name, 'belly shooter', from the concave rest at its rear end, against which the archer braced his stomach while drawing (or 'spanning') the bow. The stock of the weapon comprised two features that were crucial to the development of the catapult: the *syrinx* (or 'pipe') and the *diōstra* ('slider'). The *syrinx* was the body of the weapon; the bow was fixed to the front of it, the concave rest to the rear. The *diōstra* was a somewhat shorter board, dovetailed on top of the *syrinx* so that it could slide forwards and backwards freely; attached to its rear end was a mechanism, which incorporated a 'claw' for gripping the bowstring and a trigger to release it again.

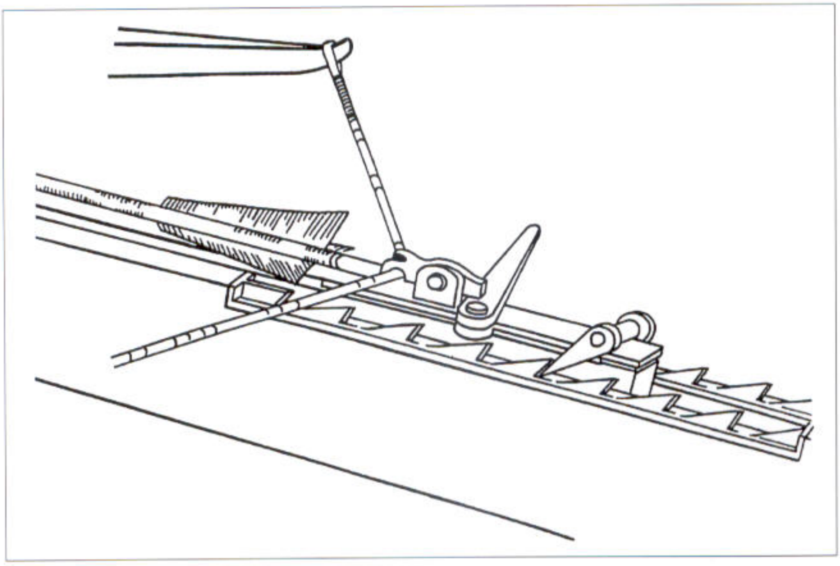
With the weapon at rest, the archer slid the *diōstra* forwards along the *syrinx* until the trigger mechanism fell level with the bow-string, whereupon the 'claw' was engaged. Propping the front of the *diōstra* against an immovable object, such as the ground or a wall, the archer then brought his whole weight to bear on the stomach rest. The archer's weight forced the *diōstra* back along the *syrinx*, pulling the bow-string with it, and thus spanning the bow. This was necessary because the bow was too powerful to be drawn by hand.

With the bow at full draw, the weapon could be lifted into a firing position. This must usually have involved propping it on a wall, given the weight and bulk of the machine; otherwise, the archer would have required a portable prop, similar to those used by musketeers in the 17th century. It only remained to place the arrow on the *diōstra*, which had a ready-made groove cut along its full length. Pulling the trigger caused the claw to release the bow-string, thus firing the arrow. The whole process could then be repeated.



Heron drew his description of the *gastraphetēs* from the work of Ctesibius, who worked in Alexandria around 275 BC. Unfortunately, Heron omits all measurements, but as a hand weapon the *gastraphetēs* was probably slightly shorter than a metre. (Author's drawing)

The classicist Sir William Tarn believed that it was this weapon that Dionysius's engineers had invented, an assumption with which the British scholar Eric Marsden underpinned his study of ancient artillery. However, the German artillery officer Major General Erwin Schramm preferred to take Diodorus at his word when he placed the invention of the 'catapult' in the opening years of the 4th century. For Schramm, this was the full-blown torsion catapult, not its composite bow-based predecessor. There is a third possibility, though. Biton actually calls the



The trigger mechanism of the *gastraphetēs*, mounted at the rear of the slider. On either side, a pawl engaged with a linear ratchet to hold the slider in position and prevent it shooting forwards unexpectedly. Here, the trigger can be seen wedged beneath the claw, forcing it to grip the bow-string. Pulling the trigger allowed the claw to flip up, releasing the bow-string. (© D. Baatz)

gastraphetēs-type machine a 'catapult' (*katapeltikon*); if Zopyrus or his colleagues had presented this little-known weapon to Dionysius in 399 BC, we can forgive ill-informed witnesses for imagining that it had just been invented.

Advanced bow-machines (Plate A)

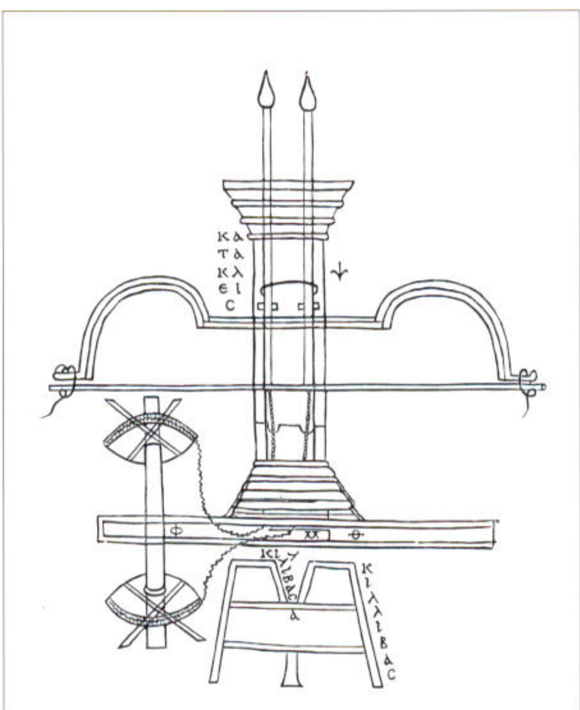
It certainly seems that bow-machines were known prior to 399 BC. Biton describes two machines designed by Zopyrus, one at Cumae, perhaps in connection with the Sabellian conquest of 421 BC, and the other at Miletus, probably prior to the Persian annexation of the town in 401 BC. The first, the so-called mountain *gastraphetēs*, had a 5ft (1.5m) stock and a 7ft (2.2m) bow; the second had a 7ft (2.2m) stock attached to a 9ft (2.8m) bow, and could apparently fire two missiles at once. Such unwieldy machines could never have been used as hand weapons. Quite apart from the large dimensions and increased weight, the bows would have been far too powerful for spanning by body weight alone. However, Zopyrus incorporated two elements that would eventually enable the leap to the torsion catapult: the winched pull-back system, necessitated by increasingly powerful bows, and the stand, which made heavier machines practicable.

In general, Biton's text is seldom clear enough to support unequivocal interpretation. The design of the bow-machine's stand is a case in point. The Miletus machine allegedly sat on a 1ft-high (0.3m) 'pedestal' (*basis*), 9ft (2.7m) long by 3ft (0.9m) wide, surmounted by a 'trestle with a height of five feet [1.5m]', but Biton later states that the trestle measured 3ft (0.9m). Schramm believed that this statement was an error introduced by monks copying and recopying the Greek text down through the ages, and that Biton had originally specified a 5ft trestle with three feet; in other words, a tripod. But a 5ft tripod sitting on a 1ft pedestal would have made the machine over 2m high, placing the trigger out of reach above the gunner's head. Schramm reasoned that Biton must simply have meant a tripod high enough to raise the *gastraphetēs* 5ft above ground level.

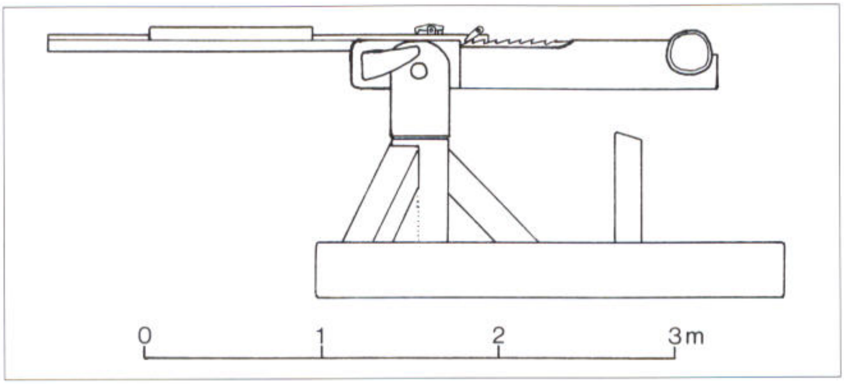
Besides the pedestal and the trestle, Biton mentions another element in his description of the Miletus stand: a 2ft-high (0.6m) vertical pillar, placed centrally on the pedestal. Schramm had already departed from Biton's description, visualising the trestle with a tilt-and-swivel bracket on top, which he fixed to the *gastraphetēs* just behind the bow. This arrangement left the rear of the weapon unsupported, so Biton's pillar was shifted back along the pedestal.

When Marsden came to analyse the same text, he attempted to rationalise Biton's measurements by suggesting that the tripod's legs were each 5ft long, but were excessively splayed on a peculiar Y-shaped base. He restored the vertical pillar to the mid-point of the base, where it functioned as a central support for the tripod, but he retained

This 11th/12th-century manuscript illustration of Zopyrus's *gastraphetēs* shows the component parts from different angles. As with other manuscript drawings of Biton's machines, it is difficult to identify any elements that may have survived from the author's original diagram. (C. Wescher, *Poliorcétique des Grecs*, Paris, 1867)



Schramm's tilt-and-swivel bracket, which he, too, attached to the front of the *gastraphetēs,* near the bow. This was essentially Schramm's design, minus the rear pillar. But, having removed this rear pillar, Marsden was obliged to invent a strut to fulfil the same function.



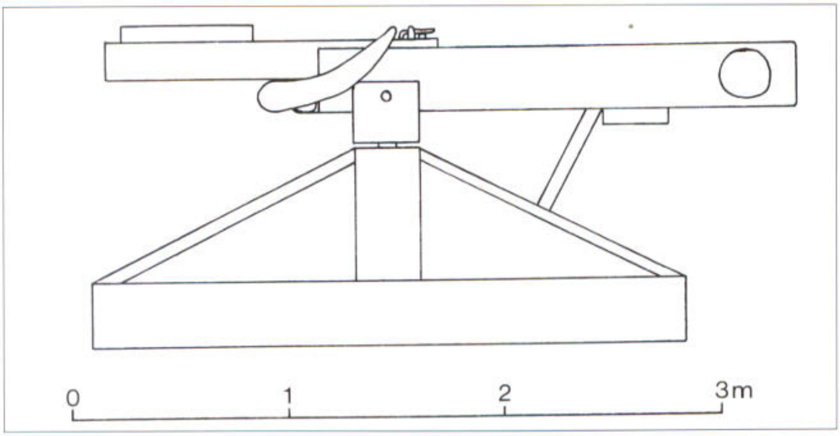
Schramm's interpretation of the Miletus *gastraphetēs* results in a solid, workmanlike machine, but he departed from Biton's description in several key areas. The raised block that can be seen on the slider is perforated to guide the twin arrows. (Author's drawing, after Schramm)

It is worth noting that Biton does not mention a tilt-and-swivel bracket in connection with the Miletus machine, nor does he mention a rear strut. However, his instructions for the Cumae machine (the so-called mountain *gastraphetēs*) add an interesting item. Here, from the outset, he refers to two trestles – a 5-footer (1.5m), equipped with a 'bowl-shaped bracket' (*agkōna kratēra*), and a 3-footer (0.9m) – both sitting on a 1ft-thick (0.3m) pedestal. As with the Miletus machine, Schramm reasoned that the main trestle of the mountain *gastraphetēs* should be high enough to raise the stock 5ft above ground level. Similarly, he envisaged the second trestle holding the rear of the weapon 3ft off the ground, thus imposing a peculiar angle of rest on the stock, which he claimed was beneficial to the winch operator. Finally, he interpreted the enigmatic 'bowl-shaped bracket' as the same tilt-and-swivel joint that he had added to the Miletus machine. Again, he fastened this bracket to the *gastraphetēs* near the front of the *syrinx,* although Biton specifies a position 4ft (1.2m) 'from the face [*prosōpon*]'. Schramm argued that this meant 4ft from the front of the *diōstra* when fully extended beyond the *syrinx.*

Marsden seized on the 'bowl-shaped bracket' as a precursor to the torsion catapult's *karchēsion,* which he translated as 'universal joint'. This was a tilt-and-swivel mechanism, expressly linked with the elevation and traversing of the catapult in Heron's *Belopoiika.* But Biton gives no indication that his bow-machines were intended to perform in the same way. Marsden also believed that the two bow-machines' stands were more or less the same. For example, he interpreted the rear 'trestle' of the Cumae mountain machine as a strut, like the one he had added to the Miletus machine; but he could not fashion a Y-shaped base-platform out of the shorter Cumae measurements (5ft by 3½ft/1.5m x 1.1m).

There is no neat solution to these problems. Although Schramm's reconstructions have an elegant functionality, this has been achieved at the expense of accuracy. Equally, Marsden's

Marsden's interpretation of the Miletus *gastraphetēs* is very similar to Schramm's, except for the stand. Here, the three legs are splayed, two to the front and one to the rear, on a Y-shaped base; an additional strut is required to support the stock of the machine. (Author's drawing, after Marsden)



frequent departures from the text were criticised as 'high-handed' by the Danish scholar Aage Drachmann. The addition of the tilt-and-swivel joint is particularly problematic, as it may not be the same as Biton's 'cup-shaped bracket' and, even if it is, should apply only to the mountain *gastraphetēs.*

Early artillery fortifications?

Prior to his death in 367 BC, Dionysius of Syracuse had enjoyed over 30 years of friendship with Sparta, and had latterly made overtures to Athens. There are a few hints that, perhaps as a result of these links, news of the bow-machine had travelled to mainland Greece. In particular, a 'catapult arrow' (*katapeltikon belos*) was apparently displayed at Sparta around this time, to the general dismay of the observers. However, the literary accounts of the period carry no reports of the bow-machine's use. Consequently, scholars have turned to archaeology to fill the void, claiming that fortifications erected in central Greece in the mid-4th century show signs of having been designed for bow-machines.

Marsden had already reasoned that the presence of shuttered windows, as opposed to arrow slits, in the upper storeys of towers indicated that they were designed for catapults. Developing this theme, the American historian Josh Ober re-dated several Theban and Athenian towers to the 360s BC, and linked them with the deployment of bow-machines. Basing his theory on small weapons with 6½ft (2.0m) stocks and 5½ft (1.7m) bows, he found that the average chamber size of roughly $5.5m^2$ could accommodate two of these. But, besides making an unimpressive artillery battery, two machines are far fewer than the number of windows would suggest.

The great corner tower of the Athenian fort at Aegosthena, dating from 343 BC, is exceptional in this regard; the generous provision of windows in the $7.5m^2$ upper chamber suggested to Marsden that it was designed for artillery. But, if so, it would seem to have been poorly planned, for only two of the three windows on each side can be used by bow-machines, the third window being obstructed by the machines on the neighbouring wall. Equally, deploying catapults some 53ft (16m) above ground level may not have been the best use of such machines, and the tower's extreme height was probably to facilitate long-range surveillance. Of course, when under attack, archers and other missile troops would surely have made full use of the windows.

A tower from the fortifications at Aegosthena, thought to have been built by the Athenians around 343 BC. The top floor is often said to have accommodated catapults, because it has three windows (approx. 0.8 x 1.1m) per side. (A. W. Lawrence, courtesy of the Conway Library, Courtauld Institute of Art)

THE ARROW-FIRING CATAPULT OF THE GREEKS

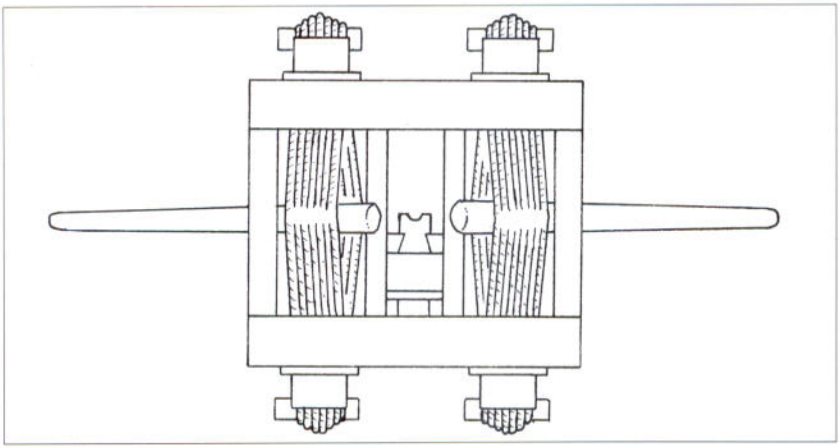
4th-century developments

The major advance in catapult design involved the replacing of the composite bow with a pair of torsion springs. If Dionysius's engineers really did make a technological breakthrough, it was surely this. However, it must have taken years of trial and error to arrive at the optimum design. Heron emphasises this for Roman readers in his edition of Ctesibius's 300-year-old work: 'You should know that the codification of measurements came from actual experiment. Earlier engineers, who had only shape and plan in mind, were not well known for the firing of their missiles, because they used unsuitable proportions. Those who came after, by reducing some elements and increasing others, brought harmony and efficiency to the devices I am speaking about.'

Dionysius allegedly fielded 'catapults of all kinds', which presumably included the *gastraphetēs* and the different varieties of bow-machine, alongside any experimental torsion machines that may have existed. Oddly, after reporting that Dionysius used the *katapeltikon* to great effect in his siege of Motya in 397 BC, Diodorus makes no mention of the weapon in the tyrant's subsequent campaigns. It seems unlikely that the bow-machines suddenly disappeared, and they surely continued in use, at least until the full flowering of the catapult made them redundant.

The new torsion weapon does not seem to have reached fruition until the middle of the 4th century. Catapults (*katapaltai*) are briefly mentioned in the *Siegecraft* (*Poliorkētika*) of Aeneas Tacticus, a treatise of roughly 350 BC written from the defenders' point of view, but they are firmly installed in the besiegers' mobile towers. Likewise, in the wealthy and progressive city of Athens, routine training in the use of catapults was not introduced until the 330s BC, a date at which evidence begins to accrue for the storage of these weapons in and around the city. By that time, the torsion catapult had already appeared elsewhere, and scholars have assumed that its testing ground was Macedon, kingdom of Philip II and his son, Alexander the Great.

It is true that catapults became a regular fixture in Alexander's siege-train, but we know of only one occasion when they were definitely used by



The spring-frame (*plinthion*) of an arrow-firing catapult was designed to hold the two torsion-springs under extreme stress. The *syrinx* fitted into the gap between the two springs, forming a window (*dioptra*) up above, through which the gunner could take his aim. (Author's drawing)

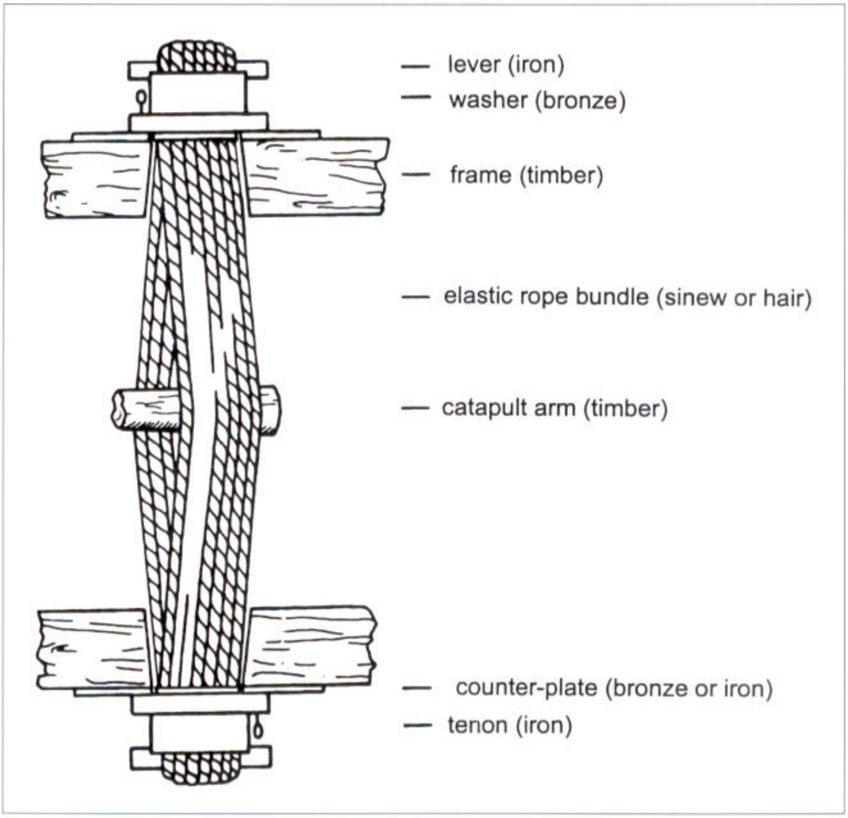
his father. In 340 BC, at Perinthus in present-day Turkey, Philip deployed 80-cubit (37m) siege-towers and rained arrows down onto the battlements from 'many arrow-firers of different kinds'. The Perinthians, for their part, received catapults from their allies in nearby Byzantium, and when Philip attempted simultaneously to besiege that town, he overstretched himself and had to withdraw from both. Some years earlier, while besieging Methone in northern Greece, he had lost his right eye to an arrow, but the tale that it was fired by a catapult is a later fabrication.

It must be admitted that the argument linking Philip with the development of artillery is a little threadbare, but at least he is known to have been an enthusiastic patron of military engineering. Polyidus the Thessalian and his apprentices, who developed the siege-towers and battering rams for the king (see the companion volume to this title, New Vanguard 78: *Greek and Roman Siege Machinery 399 BC–AD 363*, Oxford: Osprey, 2003), may well have been involved in perfecting the torsion catapult.

The arrow-firer in the 3rd century (Plate B)

The rules for constructing a serviceable torsion catapult appear to have been standardised by around 280 BC, if not before. In the later 3rd century BC, a Byzantine engineer named Philon wrote about artillery and siegecraft in his *Mechanical encyclopedia* (*Mēchanikē syntaxis*). He indicates a lengthy developmental process, which resulted in the codification of a set of rules: 'others later theorised from earlier mistakes and, from subsequent trials, observed a standard element which would represent the basic principle and the method of setting about construction.' He placed this major breakthrough at Alexandria. Although the crucial date is not given, his reference to research being sponsored by 'ambitious kings' suggested to Marsden that the period in question spanned the reigns of Ptolemy I (reigned 323–283/2 BC) and Ptolemy II (283/2–246 BC).

The torsion-spring of a catapult was formed by repeatedly feeding a length of hair- or sinew-cord through the cross-pieces of the spring-frame. At each end of the spring, the cord ran through the washer, around the lever, and back through the washer. (© D. Baatz)



During the latter's reign, the mechanical genius Ctesibius rose to prominence. Although he left no writings, he is often mentioned by later engineers. Indeed, it was a summary of his work on artillery that Heron published during the reign of Nero (*c.* AD 60). Philon even claims to have interviewed men who knew Ctesibius and were familiar with his machines. But it would seem that artillery construction had long since been standardised by his day, as he felt at liberty to explore new developments, such as the compressed-air catapult and the bronze-spring catapult (neither of which seems to have been put to military use).

The design of the arrow-firer: the spring-frame

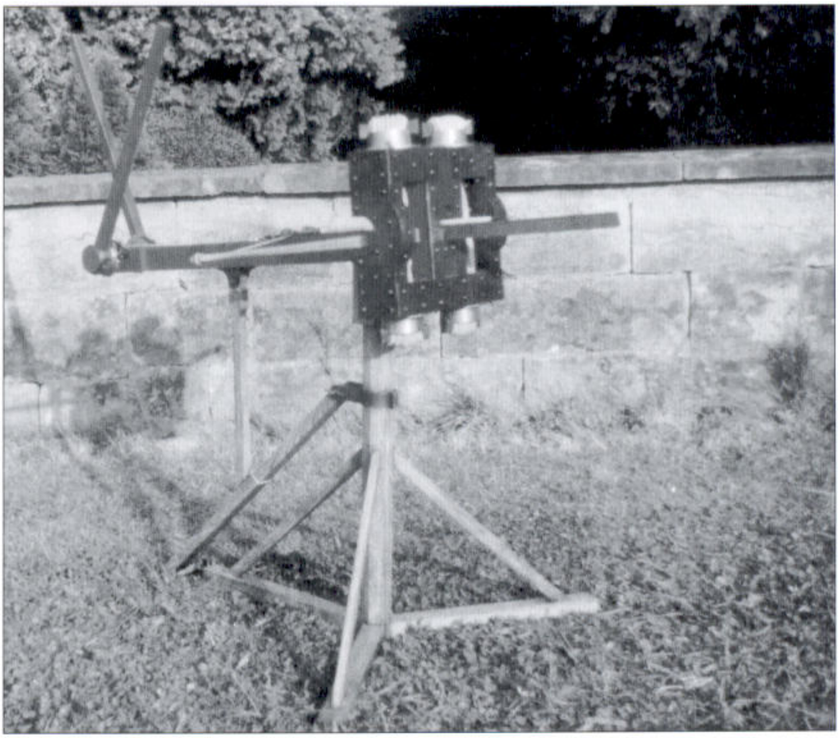
Whereas the *gastraphetēs* derived its power from a composite bow, the catapult used a pair of vertical torsion-springs. Each spring took the form of a skein of hair- or sinew-cord, held under tension in a wooden frame; a solid wooden arm was inserted through each skein. In order to emulate the action of a bow, the ends of the outward-swinging arms were connected by a bow-string. The action of pulling this string ('spanning' the catapult) drew the arms back and twisted the skeins; on release, they sprang back into position.

The wooden frame that replaced the bow of the *gastraphetēs*-type machine followed a standard design described by both Heron and Philon. Four uprights, arranged in two pairs to straddle the stock of the catapult, supported a top and bottom cross-piece (*peritrēton*). Each cross-piece had two large holes bored through for the torsion-springs, and a swivelling bronze washer (*choinikis*), with a horizontal iron lever (*epizygis*) on top, sat in each hole.

Each torsion-spring consisted of a single length of hair- or sinew-cord, threaded through the washers in the frame and around the levers to form a tight skein. Every time the cord was fed through, it was pulled tight on the windlasses of a separate machine called a stretcher (*entonion*) until it had lost a third of its diameter; the experienced engineer checked by plucking it and listening for the correct musical note. The whole tedious process was continued until no more cord

Plaster cast of the so-called 'Cupid Gem', perhaps dating from the 1st century BC. Cupid is operating a two-handed winch to span the catapult. A ratchet-wheel and curved pawl are plainly visible on the side of the machine, and the pull-back rope can be followed up to the trigger mechanism. The four washers are prominent, but the springs are obscured by a large insect, which Cupid appears to be using in lieu of an arrow. (© Deutsches Archäologisches Institut, Rome)

Reconstruction of the catapult from Caminreal (Spain). The stand follows Schramm's design. The spring-frame indicates a slightly undersized 3½-span machine, designed to fire arrows around 80cm long. In tests, Schramm's 4-span catapult reached 370m, but the effects of wind-drift and air resistance make ranges in excess of about 150m militarily undesirable for the arrow-firer. (© D. Baatz)



could be forced through the washers. Philon complains that, if a spring broke, fitting a new one was very time-consuming. He also points out that the springs tended to lose their elasticity through prolonged use of the catapult, but could be temporarily tuned up by twisting the washers.

For the bow-arms, a tapering piece of solid wood was stuck through the middle of each torsion-spring, so that its thick end (the *pterna*, or heel) was gripped by the skein and its thin end stuck out to the side. The movement of the arms was limited by the placement of the spring-frame uprights. In particular, when the catapult was fired, the heels tended to crash against the inner uprights; so the farther back these could be positioned, the better, in order to increase further the arms' movement and maximise the torsion effect. At the same time, a semicircular recess was cut in the outer uprights, to accommodate the forward swing of the arms. Of course, it was not intended that the arms would hit these outer uprights, as this would surely cause them to crack; in fact, ideally the bow-string itself would halt the arms' swing, absorbing in the process any residual energy from the shot.

Greek engineers envisaged each torsion-spring as a cylinder, for which they strove to find the optimum dimensions. As they attempted to develop a universal rule, they realised that their calculations were dependent upon the size of arrow that the catapult was expected to fire; bigger, heavier arrows would naturally require a more powerful catapult, and hence larger springs. Eventually, it was agreed that the best results came from a spring whose height was approximately 6.5 times its diameter, and that the diameter should be one-ninth of the proposed missile's length.

Heron explains that the size of every component in the catapult was laid down as a multiple or a fraction of 'the diameter [*diametros*] of the hole which takes the spring'; or, in other words, the inner diameter of the washer. In short, the size of the washer was directly related to the overall size of the catapult. For example, a machine designed to fire an arrow three spans (69cm) in length had a *diametros* of four daktyls (69 ÷ 9 = 7.7cm), which thus became the basic unit of measurement for the entire catapult: the spring-frame, being 6½ units wide (the length of the *peritrēton*) and 5½ units high (the height of the uprights plus the thickness of the two *peritrēta*), was 50cm x 42cm for this size of catapult; the wooden arms, at 7 units long, were 54cm; and so on.

The design of the arrow-firer: the stock and stand

The stock of the catapult comprised the same arrangement of pipe and slider, familiar from the *gastraphetēs,* and incorporated a rear-mounted winch, like the advanced bow-machines. Heron explains that 'the whole device must be raised up on a base, so that the pull-back becomes easy to manage, and must be traversed as required and elevated, so that after placing the missile, having aligned it to the target, we may release the bow-string.'

He recognised that, prior to firing, the gunner might need to fine-tune his aim, so the junction between catapult and stand had to permit the traversing and the laying of the stock at different angles. This was achieved by means of a component called the *karchēsion,* a tilt-and-swivel joint also found on cranes. Basically, a U-shaped bracket gripped the *syrinx* of the catapult, and a horizontal axle was driven through, pinning the *syrinx* in such a way that it could be tilted up and down; at the same time, the bracket was fixed to the stand by a vertical pin that allowed the catapult to swivel. The point of attachment must have been fairly near the front of the *syrinx,* close to the spring-frame, in order to preserve the machine's balance.

The stand that Heron describes was suitable for all arrow-firers, and comprised three elements: a 1½ cubit (0.69m) vertical pillar (*styliskos*), set up on a three-legged pedestal (*basis triskelēs*); a long, diagonal 'counter-stay' (*antēreidion*), with one end hinged to the rear of the main pillar and the other resting on the ground; and a vertical 'prop' (*anapaustēria*), hinged halfway along the counter-stay, in order to support the stock of the catapult.

The only other description of a Greek arrow-firer's stand occurs in connection with a special machine called the 'many shot' (*polybolos*), devised by a certain Dionysius of Alexandria. For this machine, Philon reports that 'an upright was made with a hexagonal pillar, along whose sides, at equal intervals, small beams were fitted, on which the pillar stood, as if on a platform; the small beams were nailed through from below; and the small beams were interconnected by cross-pieces, just as tripods are by their framework.'

Schramm's interpretation of Heron's stand is now familiar from virtually every reconstruction that has ever been made. Three ground-joists (Philon's 'small beams') extended radially from the base of a hexagonal pillar. For increased stability, Schramm added three supporting legs, which he borrowed from the work of Vitruvius, a Roman engineer writing in the 20s BC. The combination of Heron's 'counter-stay' and 'prop' supported the catapult stock during the spanning process. For aiming and firing, the prop was folded down onto the counter-stay, leaving the stock in the hands of the gunner. In general, Schramm's version of the stand is perfectly functional, and was adopted by Marsden with only minor alterations.

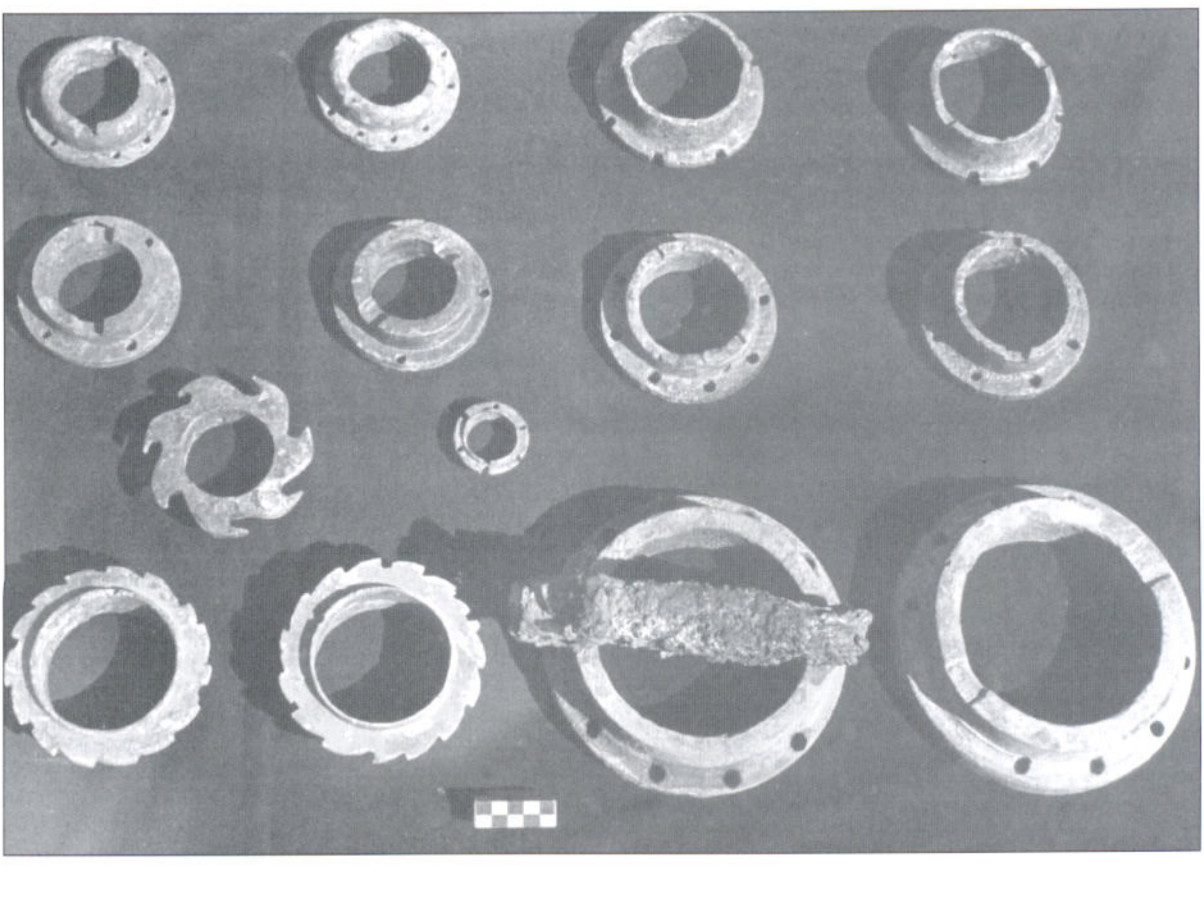
The design of the arrow-firer: the washers

The main characteristic of the torsion catapult was the set of four bronze washers (*choinikides*), which sat in the spring-frame. As they were chiefly designed to hold each spring's iron levers (*epizygides*) firmly in place, the design incorporated two rectangular notches on opposite sides of the upper rim. Equally, since they would be turned in order to squeeze more torsion out of the spring, they were circular, and a ridge projected underneath to slot into the spring-hole in the *peritrēton*. Finally, so that the washer would not slacken off after turning, it incorporated a locking device on its wide lower flange.

Their distinctive shape has led to the discovery (or belated recognition) of around 50 washers, usually as the only surviving vestige of the otherwise wooden machine. One particularly important collection comprises 21 washers, sealed in the destruction of a fortified farmstead in Epirus in north-west Greece. The lengthy chronology of the site, stretching from the 4th century down to the Roman devastation of the area in 167 BC, gives us an extraordinary insight into the development of the catapult, for the washers show a clear typological sequence.

The washers fall naturally into seven types, so that at least seven different machines could have been present. Alongside the variations in

A selection of washers from Ephyra (Epirus). From top left: row 1 shows a pair of type 4 and a pair of type 2 washers; row 2 shows the pair of type 7 and the pair of type 5 washers; row 3 shows a ratchet-wheel for a windlass and the tiny type 6 washer; and row 4 shows a pair of type 1 and a pair of type 3 washers. One of the type 3 washers still has a (badly corroded) lever in place. (© D. Baatz)



THE EPHYRA CATAPULT WASHERS

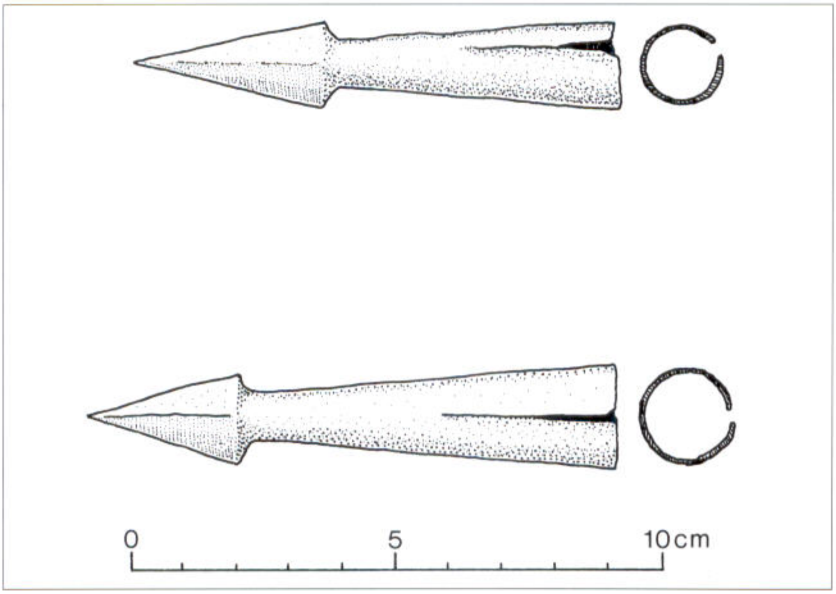
Type	Number of washers present	Average inner diameter (cm)	Corresponding arrow-length	Approx. size of catapult (length x width)*
1	4	8.4	2½ft (0.77m)	2.1 x 1.2m
2	4	8.3	2½ft (0.77m)	2.1 x 1.2m
3	4	13.6	4ft (1.23m)	3.4 x 1.9m
4	4	6.0	1ft + 1 span (0.54m)	1.5 x 0.9m
5	2	7.5	3 spans (0.69m)	1.9 x 1.1m
6	1	3.4	1ft (0.31m)	hand-held
7	2	5.6	1ft + 1 span (0.54m)	1.4 x 0.8m

* Approximate size of machine taken as 25 *diametroi* by 14 *diametroi*

diametros (inner diameter), there are also variations in the height of the washers, relative to their diameters. It has been suggested that the earliest washers were shallow and smoothly curved, and that washer profiles gradually deepened over time. But it is the style of locking device that shows the clearest development.

One set of washers (type 1) displays ratchet teeth around the flange, probably designed to lock with a pair of pawls fixed to the *peritrēton*. However, the system must have proved unsatisfactory, as the washers were later adapted by cutting four rectangular notches into their flanges. In this, they resemble a second, similarly sized set of washers (type 2), each exhibiting six, evenly spaced notches. It seems that these used the simpler method of lining up one of the notches with a hole in the *peritrēton* and driving in a rectangular peg to stop the washer turning. But there must have been a danger that the heavy torque produced by a highly tuned torsion-spring would cause the pin to jump out of the notch.

The remaining five sets of washers display an altogether more trustworthy locking method. In these, the flange was perforated with a series of pin-holes. The largest washers (type 3), whose shallow profile suggests



Two of the 27 socketed projectile-heads found at Ephyra (Greece). The larger one weighs approximately 50g, the other approx. 40g; other lighter examples were also found. The artillery scholar Dietwulf Baatz has suggested that these examples belong to a light catapult, perhaps a 3-span or 2½-footer. (Author's drawing)

Eight bronze washers, representing two differently sized catapults of the 1st century AD, were found near Cremona in 1887. This one belongs to the larger catapult. Its inner diameter of 8.9cm suggests an arrow-length of 0.80m, which conforms to no standard Roman measurement. The associated lever incorporates a thickened mid-section, buttressing it against the inner wall of the washer; this peculiar design is unparalleled. (© D. Baatz)

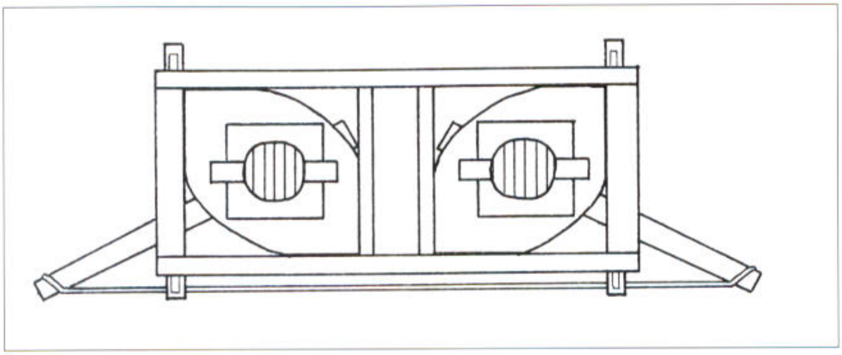
that they lie at the beginning of this new development, were provided with eight holes; one of the smaller sets (type 7), with a relatively deep profile, had only four. However, this does not mean that there were only four positions at which the washer could be pinned. Heron tells us that each washer sat on a metal counter-plate (*hypothema*) to prevent it digging into the wooden *peritrēton*, and this component would have had its own configuration of holes. The only example from Ephyra, which seems to fit the type 7 washers, appears to have had nine holes arranged around its circumference; thus, at any given moment, there was a hole in the washer within 10 degrees of a counter-plate hole.

THE STONE-PROJECTING CATAPULT OF THE GREEKS

Early developments

It seems that the first torsion catapults were designed to fire only arrows. The catapults associated with Philip of Macedon were specifically *katapeltai oxybeleis*, 'catapults for sharp missiles'; in other words, arrow-firers. It was Alexander who pioneered the use of *katapeltai petroboloi*, 'stone-projecting catapults', in siegecraft; at this early stage of development they were probably fairly lightweight machines. Yet, only 30 years later, Demetrius Poliorcetes was able to deploy monstrous machines designed to throw stones weighing 3 talents (78kg).

However, we should beware of interpreting every stone-throwing incident as evidence of these complex and expensive machines. In the ancient world, there was a long tradition of combatants throwing stones by hand, but it is usually clear from the context whether men or machines were intended. For example, the Phocian general Onomarchus is said to have deployed stone-throwing troops on a hilltop to pelt Philip's Macedonians on the plain below with rocks. Our source for this anecdote, the Antonine philosopher Polyaenus, uses the word *petroboloi,* 'stone throwers', which has frequently led to misinterpretation.



Viewed from above, the separate rhomboidal *peritrēta* of the stone-projector can be seen, held in position by a rectangular framework. The technical term for the machine, *palintonos* or 'bent spring', probably refers to the way in which the two springs have been turned away from one another to increase the angle of arm recoil. (Author's drawing)

The design of the stone-projector: the spring-frame and stock

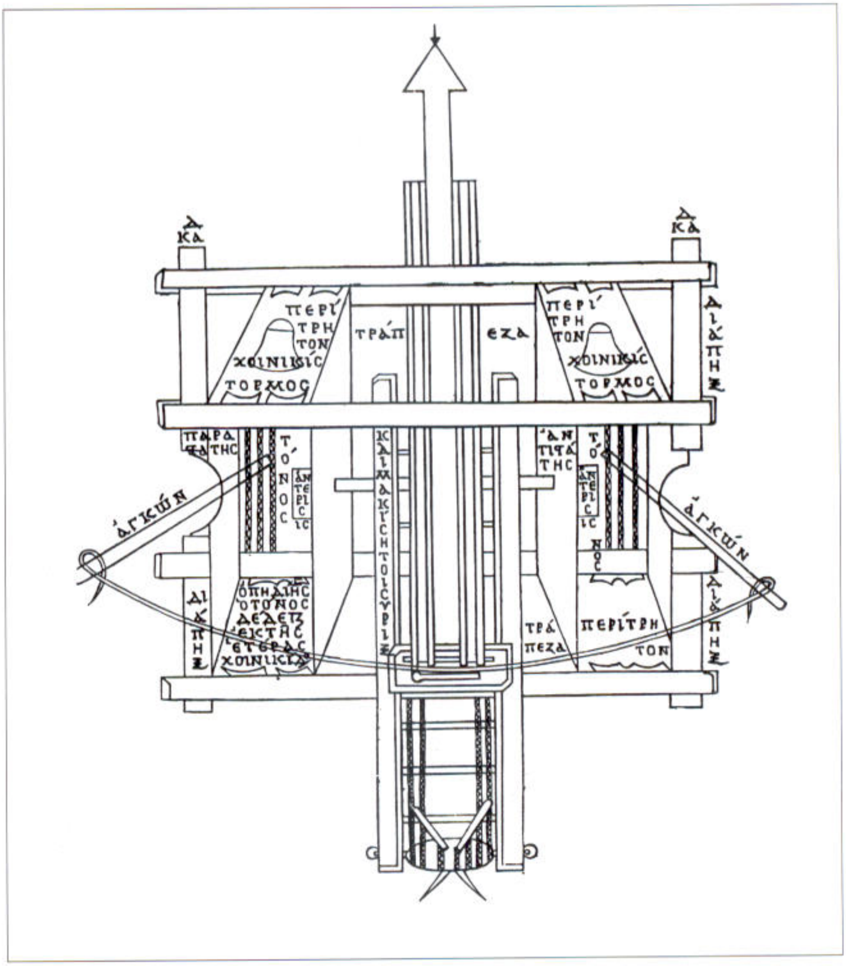
The heavier stone projectile required some modification of the original arrow-firing design. Heron explains that the frame of a stone-projector consisted of two separate torsion-springs, each with its own pair of uprights, an upper and lower *peritrēton*, and a pair of washers and levers. The two separate units were then joined together by extra woodwork, and the gap in between, for the stock of the catapult, was reinforced by a plank called the *trapeza* (table).

There was a good reason for constructing the stone-projector's frame in this way. Engineers strove to increase the arc through which the catapult's arms recoiled, in order to extract the maximum power from the torsion-springs. The so-called 'euthytone' design of the arrow-firer, whereby a single, rectangular *peritrēton* held the springs side by side, allowed a recoil of only 35 degrees. However, replacing this with two rhomboidal *peritrēta* allowed the uprights to be offset, effectively turning the springs away from one another. An angle approaching 50 degrees could now be achieved. This design was given the name 'palintone'.

Philon tells us that, according to Alexandrian and Rhodian engineers (who appear to have been the experts), the ideal stone-projector's springs were roughly nine times as tall as their diameter. As with the arrow-firer, this *diametros*, again corresponding to the inner diameter of the washer, was the key dimension for constructing the rest of the catapult. For example, the 9-diameter-high spring was achieved by making the timber uprights 5½ spring-diameters high, the top and bottom *peritrēta* 1 diameter thick, and the washers ¾ diameter high.

Along with the change in spring-frame design went a change in the design of the stock. In place of the *syrinx*, the stone-projector had a 'ladder' (*klimax*), which overlapped the *trapeza* to create a firm bond with the spring-frame. Weight was probably the issue in a machine that, even at lighter calibres, was already bigger than most arrow-firers. The structure was further braced by two struts (the *antēreides*) running obliquely from the top of the spring-frame towards the rear of the *klimax*. In place of the *diōstra,* Philon mentions a component called the 'little turtle' (*chelōnion*); naturally, given the nature of the missile, the groove along the *chelōnion* had to be wider than the equivalent feature on the arrow-firer's *diōstra*. Similarly, the bow-string must have taken the form of a strap, at least in the middle where it came into contact with the missile; curiously, Biton is the only author who calls attention to this fact, calling the component a *sphendonē* (sling) rather than a *neura* (cord).

The manuscript illustration of Heron's stone-projector demonstrates the peculiar convention (frequently encountered in ancient engineering texts) of combining several viewpoints in one diagram. The artist has attempted to show a perspective view of the spring-frames, superimposed on a plan of the catapult stock, whose laddered construction can clearly be seen. The rear-mounted windlass is shown in side elevation. (C. Wescher, *Poliorcétique des Grecs*, Paris, 1867)



The design of the stone-projector: the washers

We have seen, in the context of the arrow-firer, that the catapult was always tailored to the size of missile. This rule applied equally to the stone-projector. But, where the arrow for a particular arrow-firer was simply nine times as long as the spring-diameter, the relationship between the stone-projector and its intended missile was more complex, and can only have arisen after years of trial and error.

First, the craftsman planning to build a stone-projector had to multiply by 100 the weight of his intended missile, in minas. He then had to calculate the cube root, and increase the result by a tenth. The figure that he arrived at corresponded to the spring-hole diameter in daktyls. This complicated calculation may be expressed mathematically like this:

Diametros = $1.1 \sqrt[3]{(100 \times \text{weight in minas})}$

Thus, for a stone-projector designed to throw missiles of 10 minas (4.4kg), the spring-diameter was

$1.1 \sqrt[3]{(100 \times 10)} = 1.1 \sqrt[3]{(1{,}000)} = 1.1 \times 10 = 11$ daktyls = 21.2cm

Philon supplies a list equating standard missile weights with the corresponding spring-diameters, to save his readers the trouble of calculating complicated cube roots. One or two of his figures are obviously wrong, but the errors can be put down to careless copying of the text by hand during medieval times.

PHILON'S STONE-PROJECTOR LIST

Weight of missile Minas/talents	kg	Corresponding spring-diameter Daktyls (as per Philon*)	cm
10 minas	4.4	11.0 (11)	21.2
15 minas	6.5	12.6 (12¾)	24.3
20 minas	8.7	13.9 (14[¾])	26.8
30 minas	13.1	15.9 (15¾)	30.7
50 minas	21.8	18.8 ([19¾])	36.3
1 talent	26.2	19.9 ([21])	38.4
2 talents	52.4	25.2 (25)	48.6
2½ talents	65.5	27.1 (27)	52.3

* The figures in brackets are taken from Philon's text; square brackets indicate erroneous figures that have probably been corrupted during transmission

It can immediately be seen that we are dealing with very large spring-diameters, which in turn imply bigger washers. Even Philon's smallest machine had far larger washers than any of the arrow-firers from Ephyra. It seems that larger washers were made of wood, but they were probably reinforced with metal, as Heron advises iron-plating any points of stress on the machine.

Of course, larger washers meant larger catapults. For example, a euthytone catapult designed to fire a 4ft (1.2m) arrow was about 3.4m long; such a machine would be classified as a heavy-duty weapon. However, a similarly sized stone-projector would only manage a tiny 2.3-mina (1kg) stone. It could be argued that the labour and expense of building such a lightweight stone-projector would have been better spent on a 4ft arrow-firer.

The stone-projector from Alexander to Demetrius (Plate C)

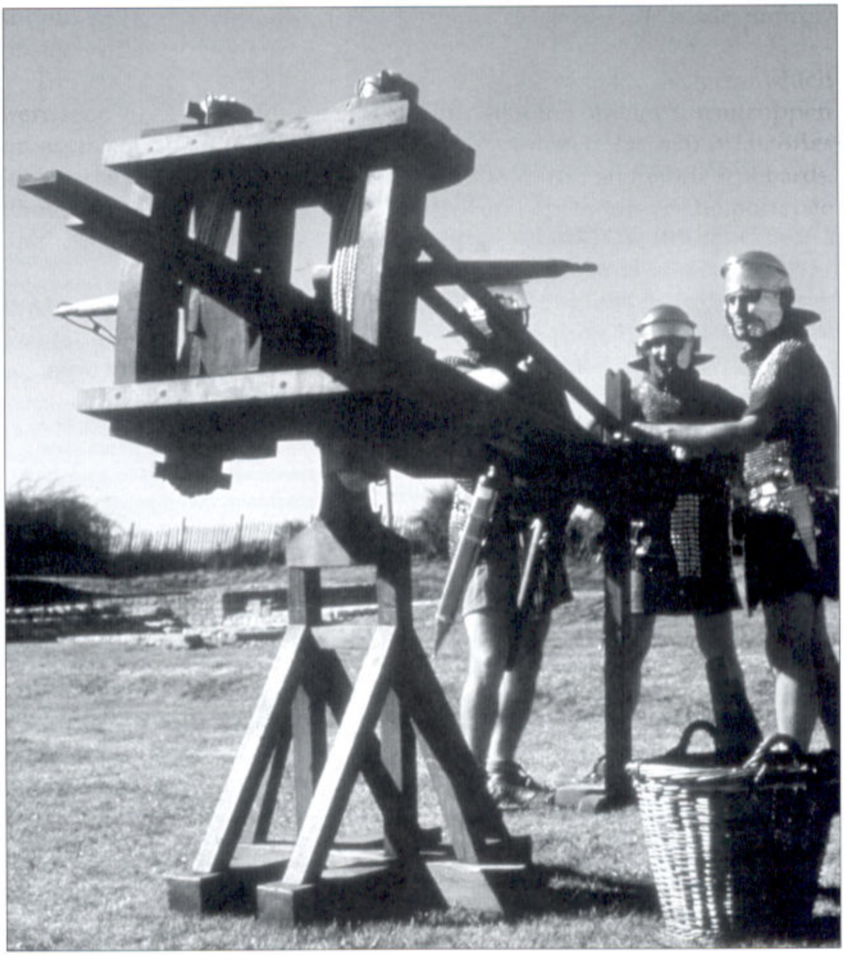
Although Alexander deployed both types of artillery at Halicarnassus (334 BC) and Tyre (332 BC), there are no further reports of stone-

A scene from the Column of Marcus Aurelius (Rome). The wagon is carrying an object that resembles the catapult stand on the 'Cupid Gem'. It has been suggested that this is a disassembled artillery-piece. (© Deutsches Archäologisches Institut, Rome) projectors until the final decade of the 4th century, when Demetrius Poliorcetes used them against the Munychia fortifications at Piraeus, then at Salamis on Cyprus, and most famously at Rhodes. However, we can look to archaeology to fill this 30-year lacuna.

A cache of stone balls, presumed to be artillery ammunition, was discovered at Salamis on Cyprus, securely dated to 311 BC by its association with Ptolemy's general, Nicocreon. Out of over 200 balls, Marsden published a representative sample of 34, of which he placed two in the 10-mina category, 11 in the 20-mina category, six in the 30-mina category, and seven in the 40-mina category. Of course, it would have been practically impossible to make each stone exactly the desired weight, and each of Marsden's categories shows some variation, as we would expect.

In devising the categories, he was principally guided by weight markings on many of the balls, comprising one or more Δ symbols (the Greek letter *delta*); these represent multiples of ten (in Greek, *deka*) in the so-called acrophonic system. However, many of the balls would appear to be marked incorrectly. For example, although the heaviest ball (35kg) was remarkably accurately coded (ΔΔT, meaning 10 + 10 minas + 1 talent = 80 minas), the next heaviest, marked ΔT (70 minas) actually weighed only 63 minas (27.5kg). And three balls weighing roughly 15 minas were each marked differently: Δ, ΔΔ, and ΔII. (The last one was perhaps a botched ΔΠ, which would actually mean 15.)

The *ballista* belonging to the Ermine Street Guard re-enactment group is roughly the size of a 2½-mina stone-projector. This was a lightweight machine, designed for missiles of around 1kg. Philon says that 2-mina machines were ideally suited to the tight confines of the tunnels used in undermining operations. (© Ermine Street Guard)



None of this detracts from the importance of the Salamis find in confirming that, during the last decades of the 4th century, stone-projector ammunition was being standardised in several different weight-classes. Unfortunately, we cannot say which calibres were favoured at Salamis, as details of only 14 per cent of the balls were published. However, it would appear that machines of 10, 15, 20, 30 and 40 minas were certainly being catered for.

The calibres of stone missiles

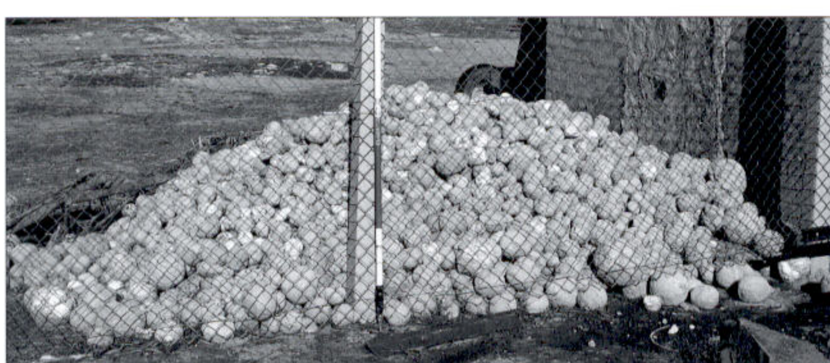
It seems that artillery manufacture was put on a new footing at Alexandria under the Ptolemies, and, when Philon wrote his *Poliorkētika* (*Siegecraft*) in the later 3rd century, towns were routinely defended, not only by arrow-firers, but also by stone-projectors. Four other assemblages of stone-projector ammunition are known.

QUANTITIES OF STONE BALLS, CATEGORISED BY WEIGHT

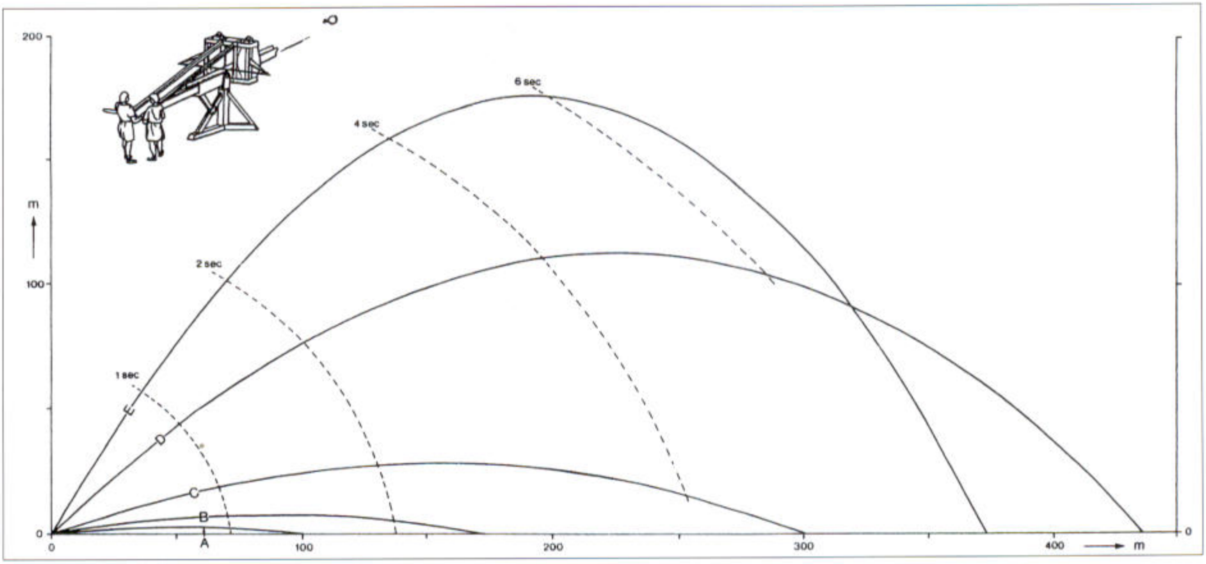
Weight (minas)	Rhodes (Greece)	Pergamon (Turkey)	Tel Dor (Israel)	Carthage (Tunisia)	Weight (kg)
3.0			6		1.3
5.0	1	1	18		2.1
8.0			11	900	3.5
10.0	46		30		4.4
12.0		1	15		5.2
15.0	56	1	23	3500	6.6
18.0		20	9		7.9
20.0	36	67	9		8.7
22.0			10	550	9.6
25.0	85		19		10.9
30.0	83	118	23		13.1
37.5		166			16.4
40.0	7	126	28	350	17.5
50.0	7		12		21.8
60.0	7	353	4		26.2
65.0		16			28.4
70.0	5			300	30.6
80.0	7				34.9
90.0	2	57			39.3
100.0	4	6			43.7
120.0		33			52.4
150.0	1				65.5
180.0	1	2			78.6

First, 353 carefully worked stones found at Rhodes display the same acrophonic markings as the Salamis balls, picked out in red paint, but they encompass a much wider range of calibres. In particular, besides the 10, 15, 20 and 30 mina categories, a 25-mina category is well represented, accounting for almost a quarter of the stones. Larger sizes, from 40 up to 100 minas (1⅔ talents), increasing in 10-mina increments, are each present in smaller quantities. But seven very large stones, weighing 2½, 3, 3½, 4½, 6, 7, and an unwieldy 10 talents, will have been for rolling (or perhaps dropping by crane), if they were intended as weapons. As for the others, the variation within each weight class is much tighter than in the Salamis assemblage, and a clear predilection for 25- and 30-mina ammunition can be seen.

The second collection comes from Pergamon in modern-day Turkey, and consists of 961 beautifully finished balls. These are more evenly spread over a range of calibres, with 166 stones representing a



Hundreds of stone balls remain uncatalogued at Hatra (Iraq), a desert town that was unsuccessfully besieged by the Romans three times. The townsfolk are said to have had machines that discharged two missiles at once. (Author's photo)



Calculated trajectories of a 30-mina (13kg) stone-projector. The maximum range is achieved with a firing-angle of 43.5 degrees (D), but the missile is airborne for 9.6 seconds, during which it will have lost almost a third of its energy to air resistance. Trajectories C (19.8 degrees) and E (60 degrees) are of questionable value for similar reasons. Trajectories A (5.7 degrees) and B (10 degrees) are far more effective: targets within 100–170m are hit with maximum impact, and with only 1 or 2 seconds warning. (© D. Baatz)

A selection of *ballista* balls discovered in the arsenal at Pergamon, demonstrating 13 different calibres, ranging from 6kg (15 minas) to 75kg (c. 3 talents). The child provides an indication of scale. (© Antikensammlung, Staatliche Museen zu Berlin, Preussischer Kulturbesitz)

peculiar 37½-mina weight class; the two heaviest stones, weighing a massive 3 talents, stand at the absolute limit of ballistic capability.

Over 200 stone balls have come to light at the Hellenistic town of Dora (Tel Dor in Israel), and perhaps belonged to the new fortifications constructed there in the third century. Some of the balls were inscribed, this time following the alphabetic, rather than the acrophonic system. In this system, E (*epsilon*, the fifth Greek letter) stands for 5, I (*iota*, the tenth Greek letter) stands for 10, and so on. One ball marked IH (*iota ēta*/10 + 8 minas) weighed 7.7kg, very nearly its marked weight; another, marked KB (*kappa bēta*/20 + 2 minas) weighed 9.5kg. The Dora stones have been convincingly divided into 14 groups, ranging from a tiny 3 minas up to 1 talent.

Carthage has also produced a quantity of artillery balls, numbering an astonishing 5,600. Again, the dating is uncertain, but they must predate the Roman destruction of the city in 146 BC. Unfortunately, only the bare minimum of detail was recorded, and the stones were each assigned to one of five categories: light (2.5–4.5kg), medium (5–7.5kg), medium-heavy (9–14kg), heavy (16–26kg), and super-heavy (28.5–40.5kg).

The smallest calibre of shot mentioned by Philon in his *Manufacture of missile weapons* (*Belopoiika*) is 10 minas (4.4kg). This belonged to a machine with springs as tall as a man; in operation, it probably required clearance of at least 6m from front to back, and 3m from side to side, and must have weighed well over half a tonne. Of course, it would be a mistake

to assume that this sizeable machine was the smallest stone projector in general use. Eighteen of the Dora balls belonged to a 5-mina category, and single 5-mina stones were discovered at Rhodes and Pergamon; some of the 900 'light' stones from Carthage may well have been of this size, too.

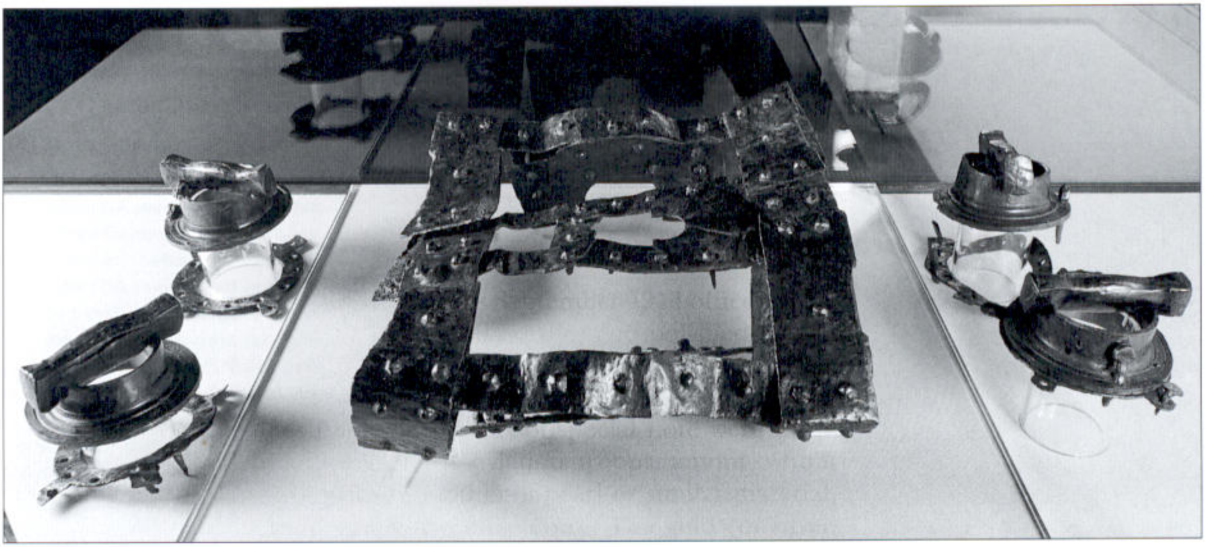
ROMAN ARTILLERY: THE REPUBLIC AND EARLY EMPIRE

The legacy of the Greeks

It is often asserted that, where machinery is concerned, the Romans displayed little inventive genius. Vitruvius, the Roman architect-engineer who wrote a work *On architecture* (*De architectura*) around 25 BC, laments the fact that so many of his sources are Greeks and so few Romans. However, the development of water power, for example, shows that the Romans were keen to adopt existing Greek technology and apply it in ever more ingenious ways.

Their acquaintance with artillery during the course of the First Punic War (264–241 BC) appears to have been brief, and their use of the weapon during the Second Punic War (218–201 BC) was the result of confiscation rather than manufacture. Some of the machines found in Roman hands were seized from the Carthaginians; for example, their capture of Cartagena in 210 BC reportedly brought the Romans a huge haul of war material, including '120 catapults of the largest sort, 281 smaller ones, 23 large *ballistae*, 52 smaller ones, and large and small scorpions'. Other catapults were no doubt requisitioned from the Greek towns of Sicily, one of the main theatres of the war. Certainly, according to Livy (a close contemporary of Vitruvius), the Roman capture of Syracuse in 211 BC

Relief carving from the Sanctuary of Athena at Pergamon (Turkey), dating from the first half of the 2nd century BC. The wooden frame of an arrow-firing catapult is prominent in the pile of weapons dedicated to the goddess. The sculptor has mistakenly represented the springs as spirals. Two massive catapult arrows are partially hidden behind the cuirass (bottom right). (© Antikensammlung, Staatliche Museen zu Berlin, Preussischer Kulturbesitz)



Catapult spring-frame discovered at Caminreal (Teruel) in Spain. The wooden frame has perished leaving only the iron plating, which was originally attached with rivets and large nails. The central hole for the slider is clearly visible, and the hole beneath must have been for the catapult stock. The machine's four washers, each with its own counter-plate, have also survived. (© Museo de Teruel; I.G. no. 8.966)

brought 'catapults and *ballistae* and all the other equipment of war', showing that the town had remained at the forefront of military technology.

Artillery in the Republic

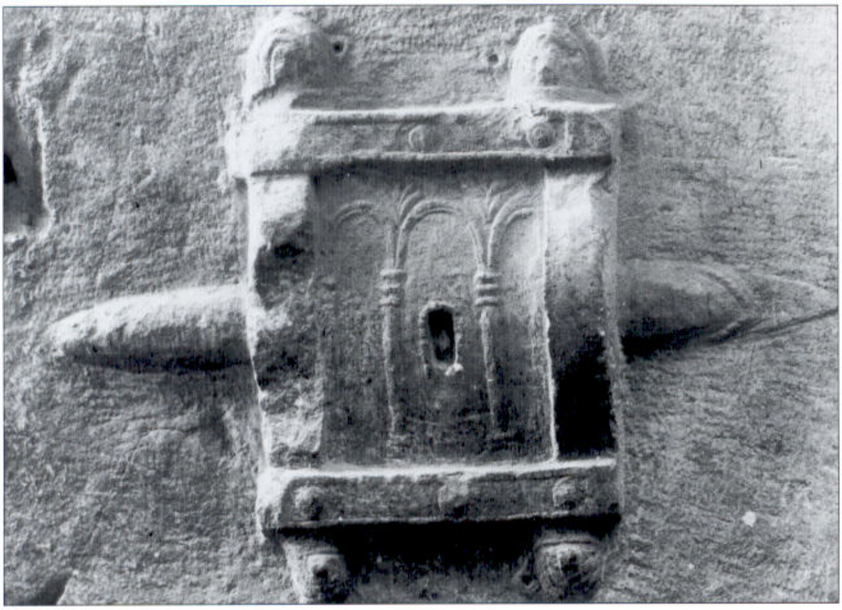
Roman stocks of artillery would have been further replenished with the booty from campaigning in Greece during wars with Macedon (200–196 BC), Sparta (195 BC), and the Aetolian Confederacy (191–189 BC). Mural artillery was becoming increasingly common in towns of the Mediterranean world, as engineers took their knowledge wherever people could pay for it. Catapults mentioned on board ships at this time were probably supplied by Rhodes and Pergamon, Rome's naval allies against Macedon, but the 'catapults, *ballistae*, and artillery of all sorts' that appeared in the triumphal procession of 187 BC in Rome were surely booty seized from the Aetolians.

Roman armies continued to use artillery in a piecemeal fashion, generally requisitioning machines whenever necessary. It is only with the campaigns of Julius Caesar in the 50s BC that we finally gain the impression of artillery as standard equipment, with at least lightweight arrow-firers regularly accompanying the legions. Although still chiefly used in siege warfare, these weapons found more imaginative employment in Caesar's hands; in defence of camp, for example, or on board ships in support of amphibious landings.

It is into this context that the most famous artillery find of all should be set. In 1912, the complete iron-clad spring-frame of a slightly undersized three-span arrow-firer came to light at Ampurias in Spain. More recently, another two spring-frames were discovered in Spain. The first, from Azaila, is apparently now lost, apart from one washer; the spring-diameter of 9.4cm suggests a four-span machine. The other, from Caminreal, is technically a 3½-span machine, but the 8.4cm washers are slightly too large, and must have been used either in error or out of necessity.

Vitruvius's arrow-firer

By the 20s BC, when Vitruvius came to describe the arrow-firer in his



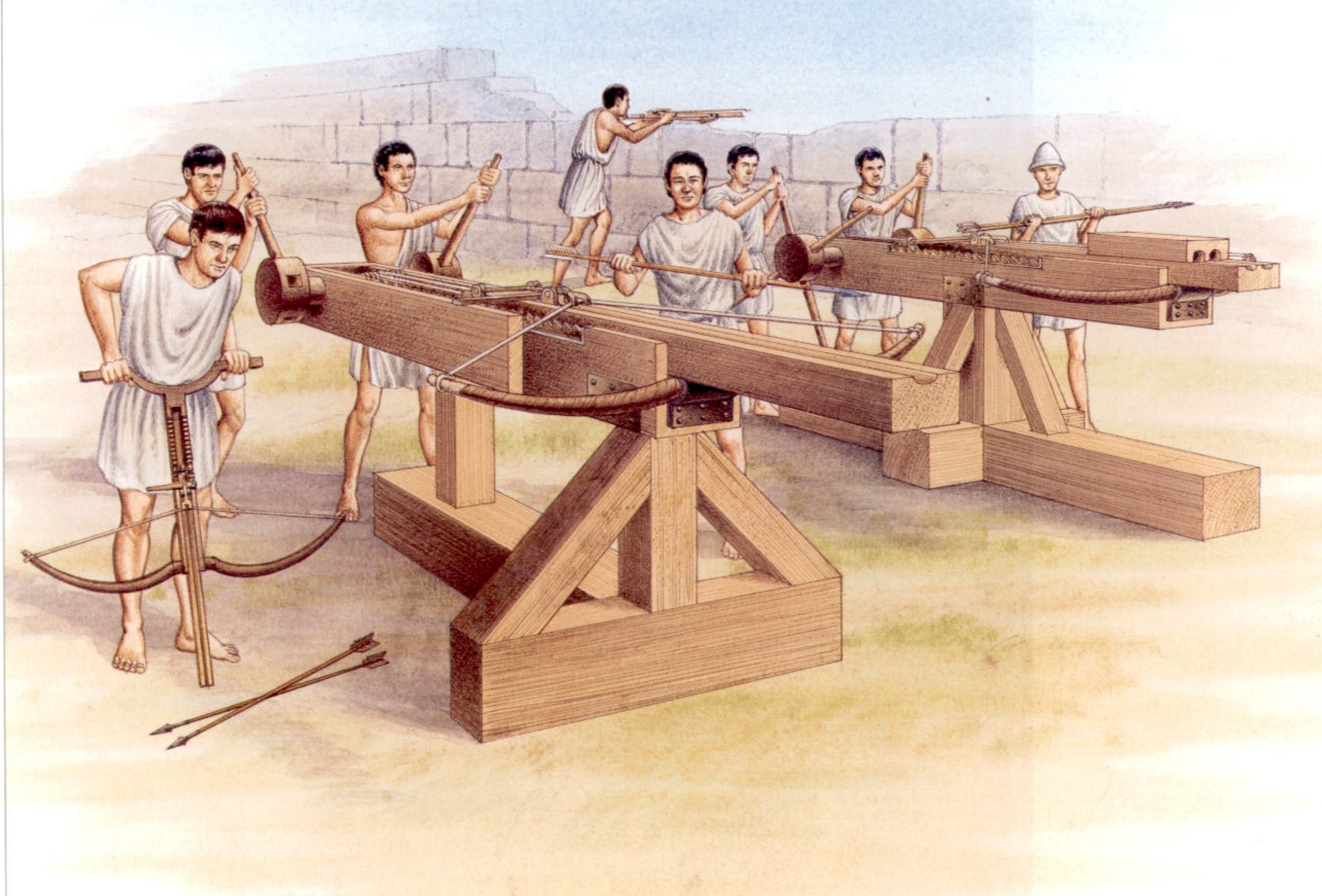
Roman catapult spring-frame, depicted on the tombstone of C. Vedennius Moderatus. Moderatus served for ten years in Legion XVI *Gallica*, before being transferred to the Praetorian Guard for a further eight years service. Although honourably discharged by the Emperor Vespasian, he was recalled for another 23 years as an engineering officer in the imperial arsenal at Rome. He was twice decorated, and died some time between AD 83 and 96. (© Deutsches Archäologisches Institut, Rome)

general survey of machinery, one or two significant changes had been made to the old euthytone. Of course, in place of the daktyl, Roman measurements used the marginally smaller digit. But, more importantly, a new Latin vocabulary was introduced for components that, until now, had been known by Greek names. In particular, the spring-diameter, *diametros*, came to be known as the *foramen*, and the washer (*choinix* in Greek) was now the *modiolus*. Also, Latin authors tended to use the collective term *tormenta* (torsion engines) for artillery, with arrow-firers individually designated *catapultae* (from the Greek term, *katapeltai oxybeleis*), except for small-calibre models, which evidently attracted the term *scorpio* (scorpion).

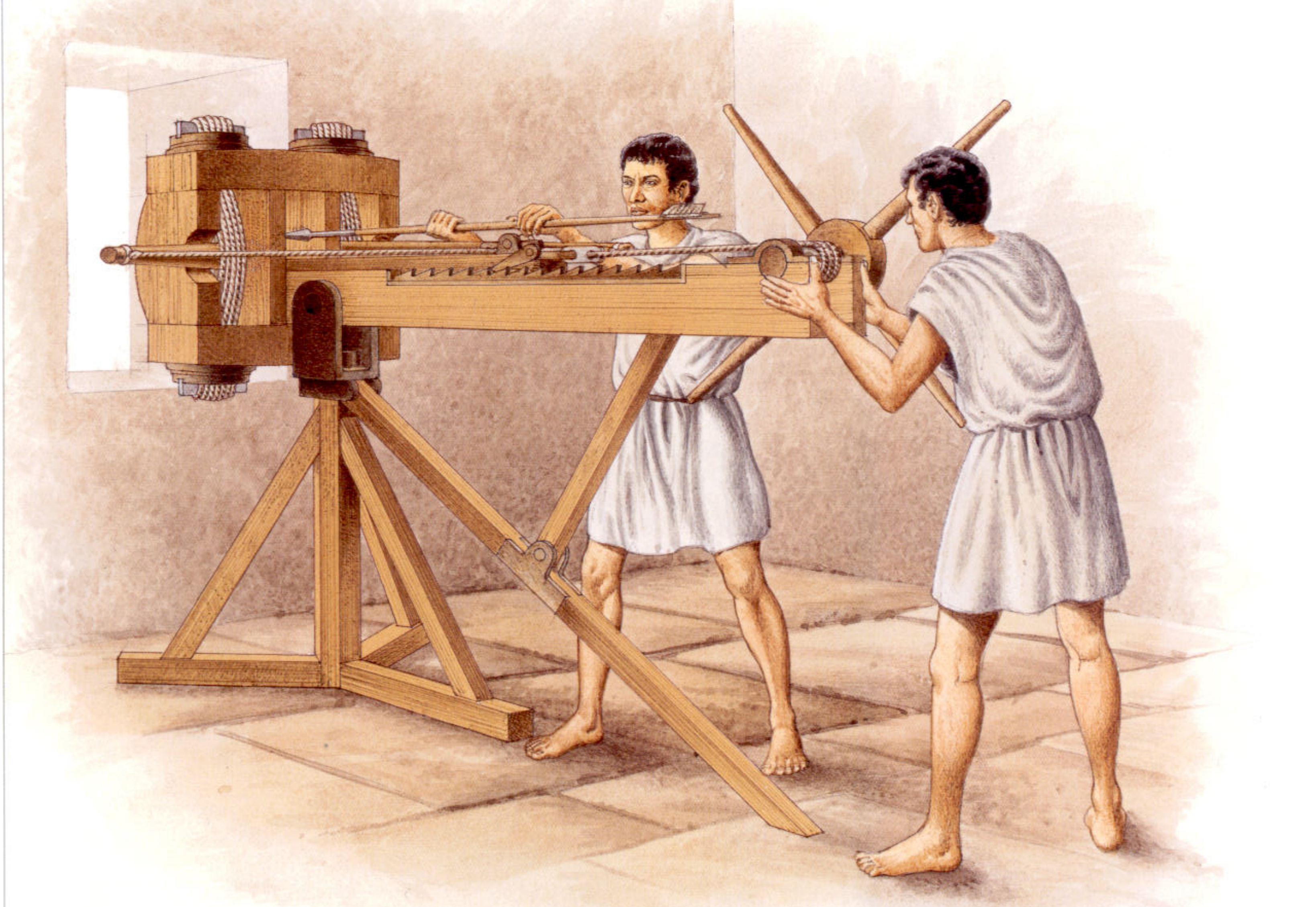
Terminology was not the only change. Vitruvius's text highlights a fundamental difference in the shape and design of the arrow-firer's spring-frame. Where Philon's uprights were 3½ spring-diameters high, Vitruvius specifies 4 diameters, and where Philon's *peritrēta* were 6½ spring-diameters long, Vitruvius specifies only 6 diameters. Thus, the Vitruvian spring-frame was narrower and taller. The saving in width was achieved by a refinement of design, as can be seen in the Ampurias and Caminreal machines. Philon's twin central uprights, which flanked the *syrinx* to create a firm bond between spring-frame and catapult stock, were removed. In their place, Vitruvius's spring-frame (called the *capitulum*, or 'capital') had a single central upright, with two apertures; one, to allow the slider to run forward, and another below it, which can only have been intended for wedging the *syrinx* (now called the *canaliculus*, or 'channel') in place.

Also, it seems that, through time, the profile of the washers became gradually higher in relation to the diameter. The type 3 washers from Ephyra, for example, are 0.4 *diametros* high; these are thought to be amongst the earliest to use the pin-hole locking system, and could be 3rd century BC in date. By contrast, the type 5 Ephyra washers are 0.5 *diametros* high, as are the slightly larger Ampurias washers; both of these are presumed to be mid-2nd century BC. The Caminreal washers, from the 1st century BC, are 0.6 *foramen* high, like the contemporary Mahdia washers, while those found at Cremona, dating a century or so later, are 0.7 *foramen*

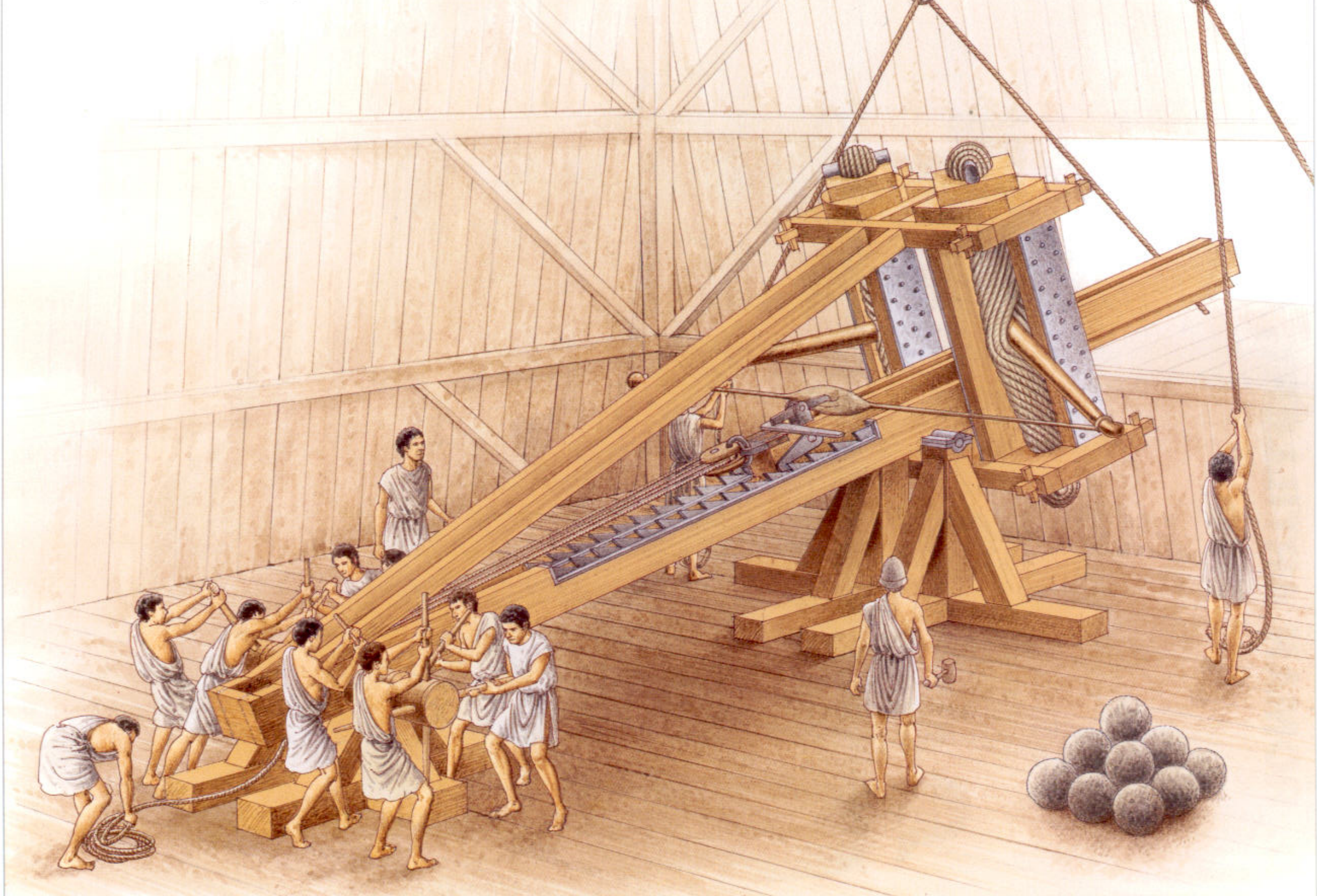
A: Early bow-machines



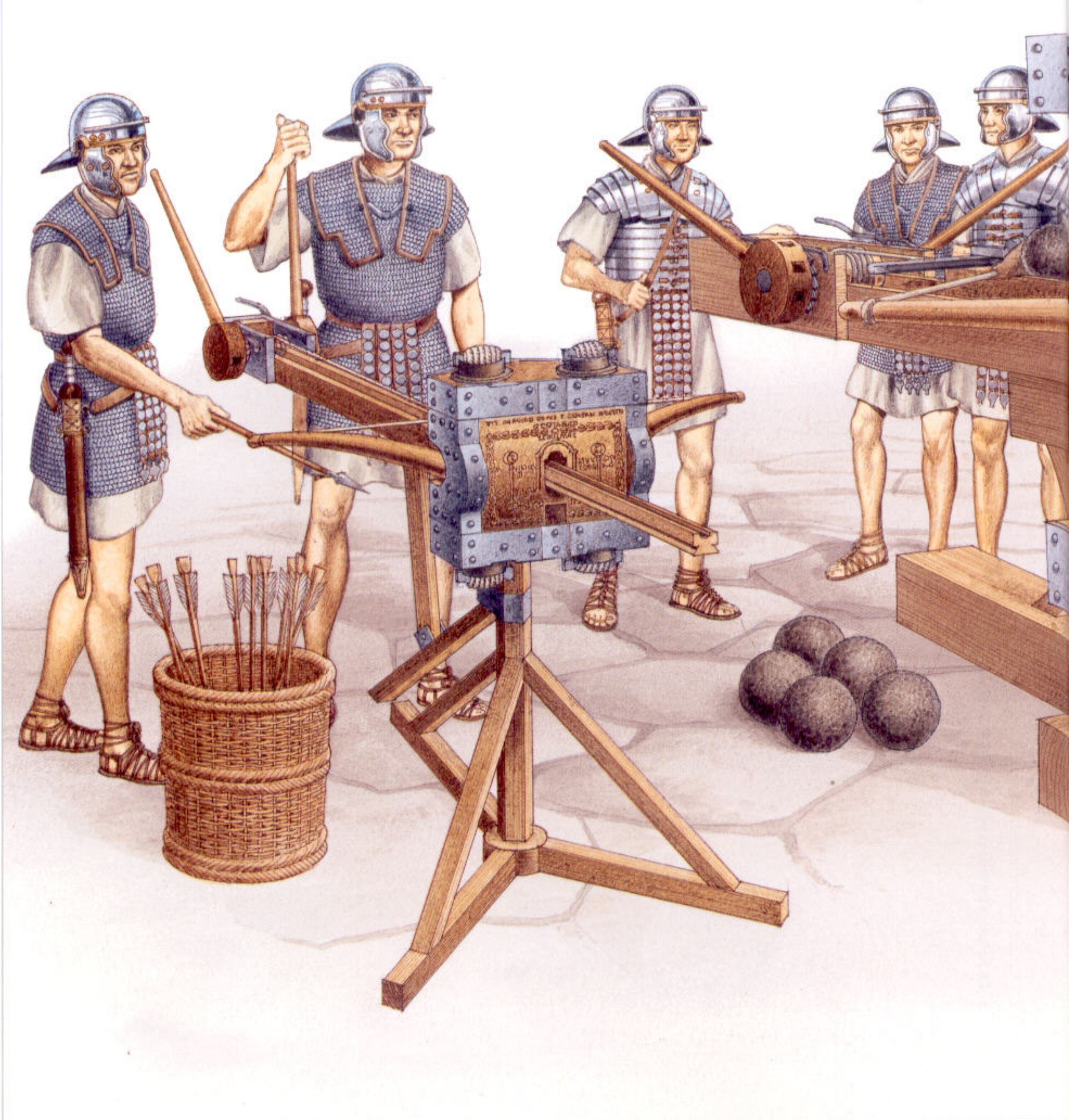
B: The fortified farmstead at Ephyra

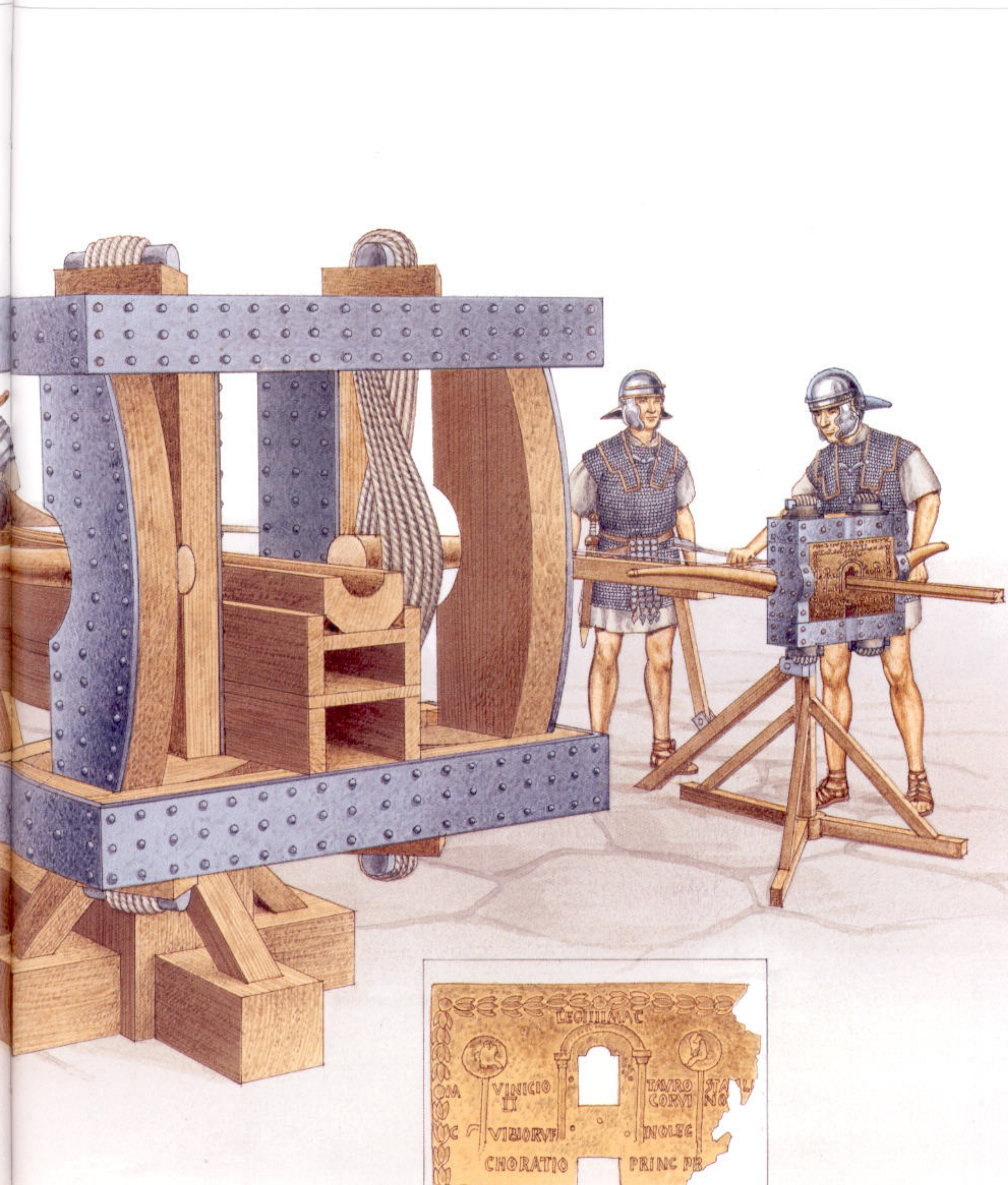


C: The 3-talent stone-projector of Demetrius Poliorcetes



D. ROMAN ARTILLERY, c. AD 69

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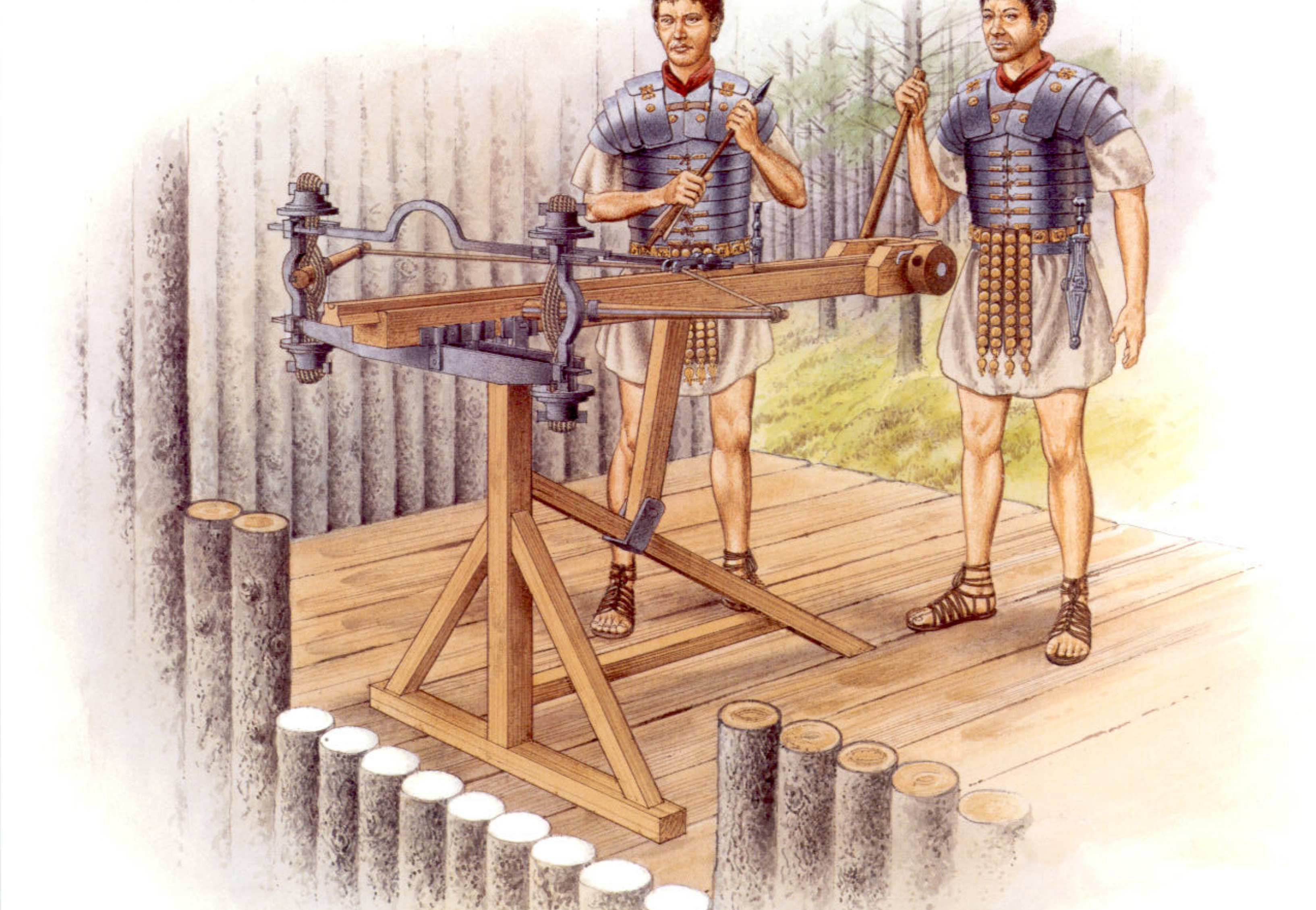
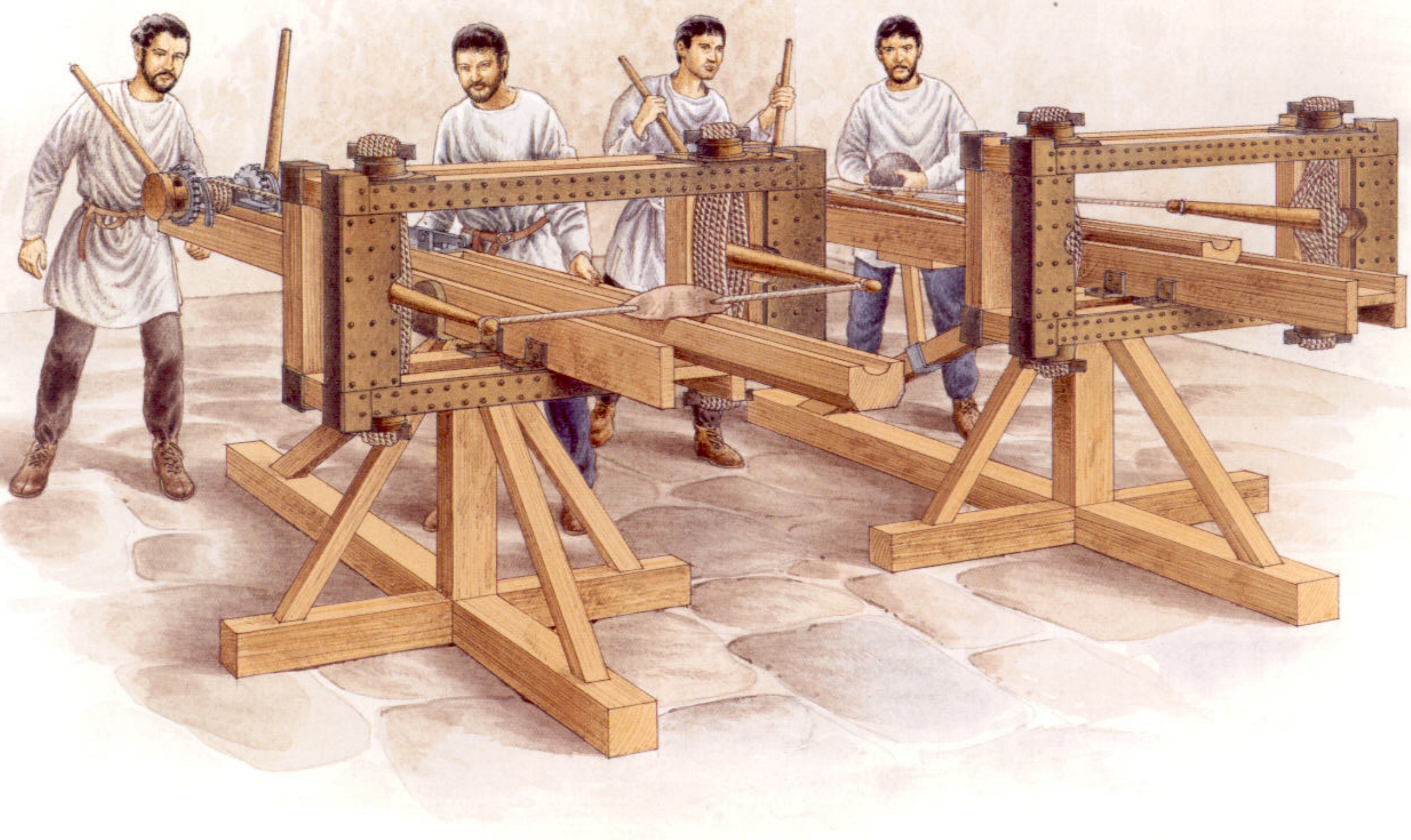
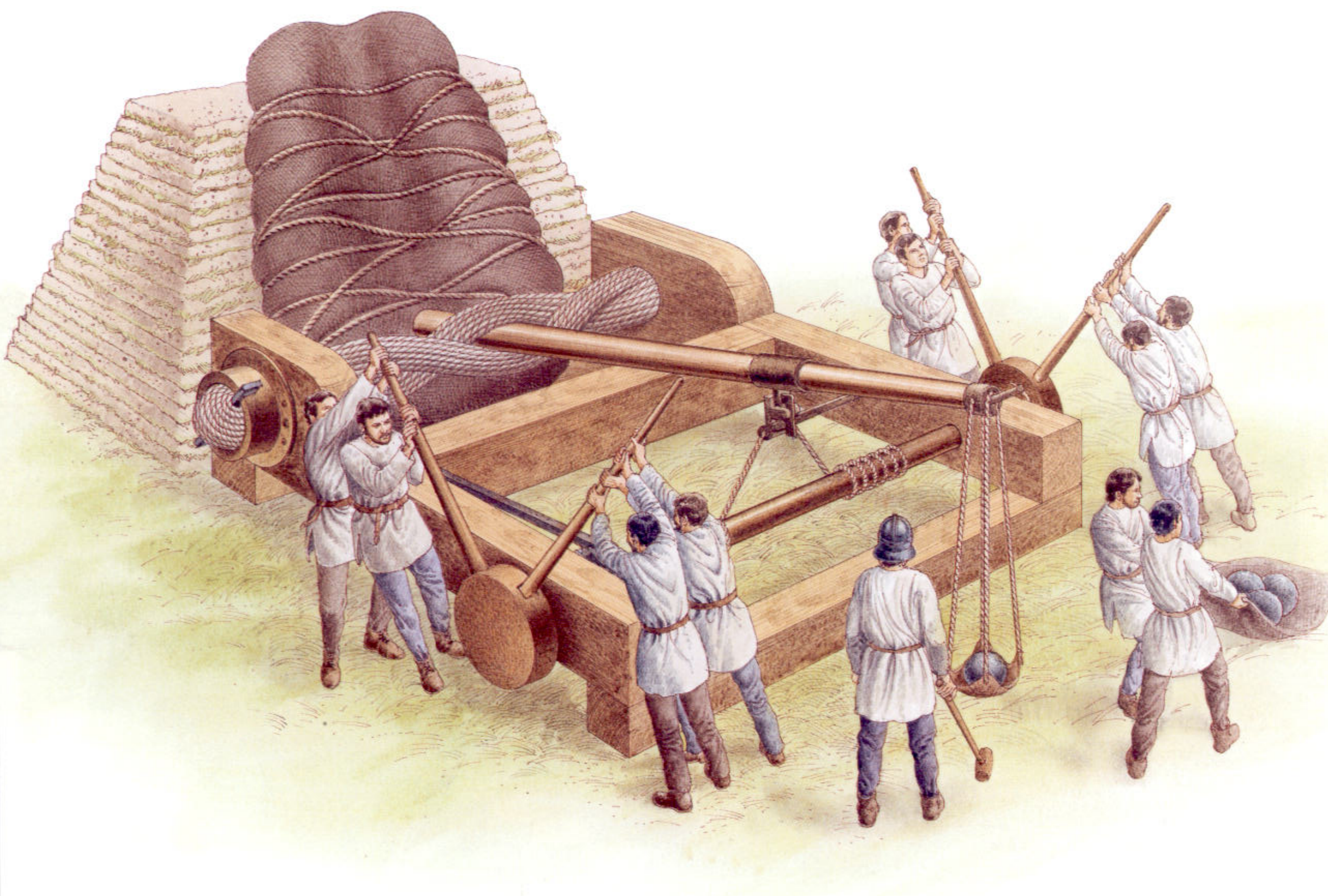
E: The new-style Roman arrow-firer



F: The Hatra *ballista*, c. AD 200



G: The *onager*



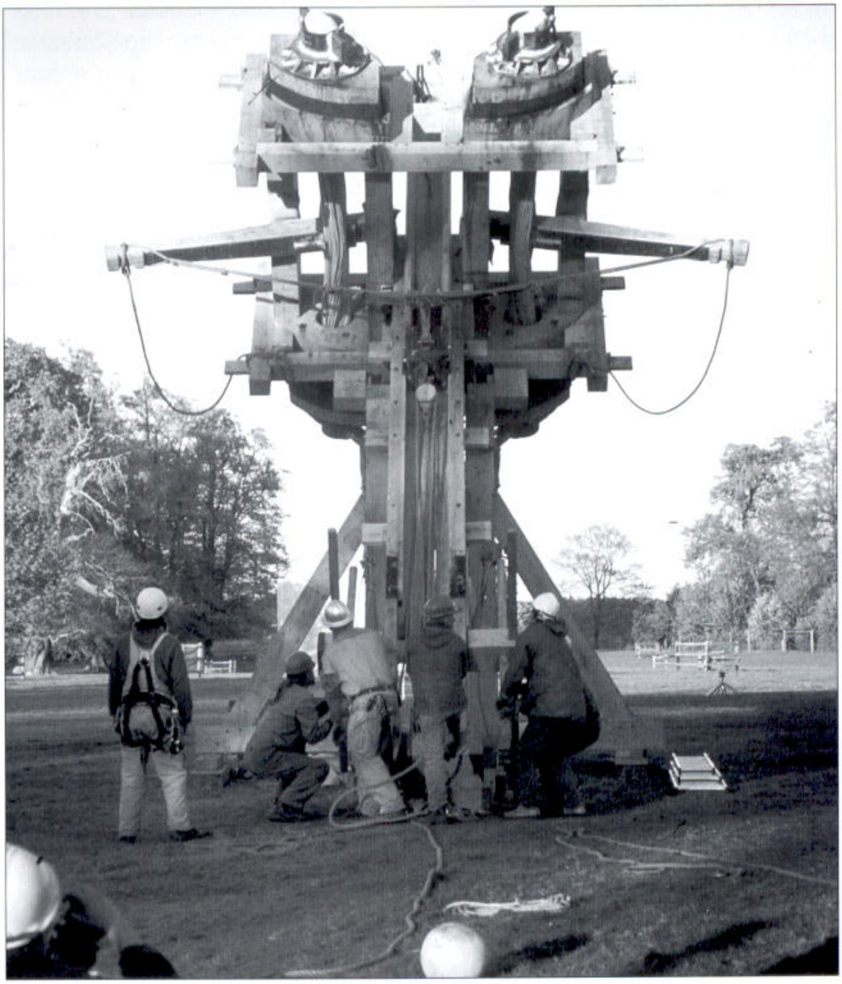
high. It is clear that the ratio between spring-diameter and washer height was gradually increasing, so Vitruvius's springs no longer adhered to Philon's proportions.

A further development involved the curving of the *catapulta*'s bow-arms, so that, at rest, the tips were further forward than their straight-arm predecessor. This effectively increased the angle of recoil from 35 degrees to 47 degrees, and meant that, on spanning, more energy could be stored in the springs. Both of these changes must have produced a more powerful machine.

Vitruvius's stone-projector

Although Greek authors continued to use the terms *lithobolos* and *petrobolos*, under the Romans the stone-projector became known as the *ballista*. For this machine, we are totally reliant on Vitruvius's description, because archaeology has failed to provide the kind of supplementary evidence that has aided the interpretation of the *catapulta*. This is unfortunate, as Vitruvius's text has suffered badly in transmission, and ambiguity surrounds the interpretation of several key passages.

One of these passages concerns the correlation of machine size to missile weight. Like the old stone-projector, each individual *ballista*



The BBC *ballista*, a one-talent stone-projector built in 2002 under the direction of Alan Wilkins, following Vitruvius's specifications. The 26kg stone missile can be seen behind the machine. The historian Josephus claims a range of 400m for this *ballista*, but Philon suggests that its effective range was nearer 160m. The reconstructed machine achieved only 90m before teething troubles forced its retiral. (© A. Wilkins.)

Front plate from a catapult of Legion IIII *Macedonica*, discovered near Cremona. It is embossed with an inscription, declaring that it was made 'in the consulship of Marcus Vinicius and Taurus Statilius Corvinus, during the governorship of Gaius Vibius Rufinus'. This places its manufacture in AD 45. The catapult was still in service 24 years later, when it appears to have been destroyed during the civil war of AD 69. (© D. Baatz)

was tailored to the appropriate missile, and the crucial measurement was, of course, the spring-diameter. Vitruvius duly lists a series of weights in *librae* (Roman pounds), each with a corresponding *foramen*. However, where Philon and Heron quote the Greek conversion formula as the source of their measurements, Vitruvius claims that he drew his information from personal experience and from his teachers, supplemented with calculations 'made by the Greeks but converted to the Roman system'.

Scholars have often thought it curious that Vitruvius's weights are paired with much smaller spring-diameters than the Greek formula would suggest. Drachmann pointed to Vitruvius's recommendation of 10-digit (185mm) springs for a 20-pound (6.55kg) missile; Philon would have used 12½-dactyl (240mm) springs for the same weight (15 minas). Drachmann realised that there were three possible explanations for this: perhaps Vitruvius was mistaken; or the Romans used under-powered machines; or their springs were somehow more efficient. He decided that, since the Roman author Heron quoted the same Greek formula as Philon, it must still have applied in Roman times, and the fault must lie with Vitruvius. But, of course, Heron was simply quoting the work of Ctesibius, from the days before even Philon; his catapults were of Greek, not Roman, design. Equally, Vitruvius is unlikely to have made such a fundamental error as quoting dimensions in *digiti* (16ths of a foot) when he meant *unciae* (12ths of a foot), as Marsden suggested. And, since it is unthinkable that the Romans would have been satisfied with under-powered machines, it seems that their *ballistae* really were more efficient than the old stone-projectors of the Greeks. How was this achieved?

Apart from possible improvements in spring material, about which we know very little, greater efficiency could have come from an increase in spring volume. Vitruvius's description shows that the *ballista*'s spring-frame was built to roughly the same proportions as the old stone-pro-jector's, but there is good reason to suppose that the springs were thicker.

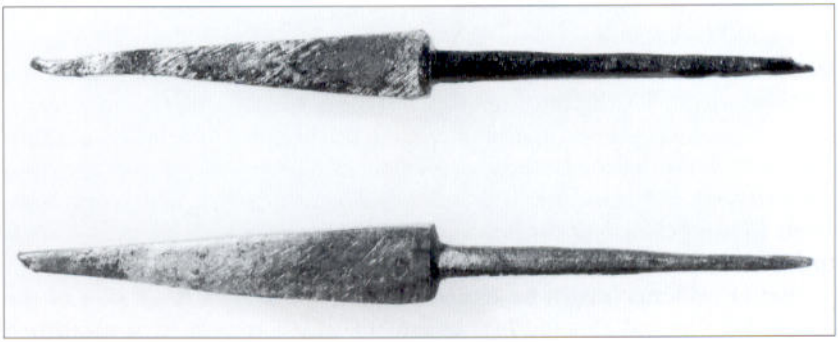
In his description of the *peritrēton* (which, for the *ballista* alone, he also calls the *scutula*, or 'diamond'), Vitruvius claims that the spring-hole should be oval rather than circular, and that the amount of elongation should offset the area occupied by the washer's lever (*epizygis*). However, Schramm pointed out that an oval spring-hole would make it impossible to turn the washer and twist the torsion-spring; he suggested that it was the upper rim of the washer that was oval, the lower rim remaining circular. Although this would be difficult to manufacture, the design makes perfect sense; in the standard cylindrical washer, the presence of the lever across the upper rim restricts the amount of spring-cord that can be forced through the spring-hole; in effect, there will always be a vacant space beneath the lever. But, by splaying the washer internally, the space occupied by the lever can be reclaimed and the spring-hole can be entirely filled with spring-cord.

It would seem, then, that more densely packed spring-cord allowed Roman engineers to build smaller *ballistae* for heavier missiles. The largest *ballista* in regular Roman service was probably the 80-pounder, which shot a 26kg missile. This was equivalent to the old-style 1-talent stone-projector, for which the Greek formula gives a *diametros* of 20 daktyls (38.5cm). (Philon's text actually reads KA, or *kappa alpha*/20 + 1 in the alphabetic system, which may have been an attempt to slightly increase the size of this heavy-duty machine.) At any rate, its springs were 3.47m high, its stock over 7m long, and the distance from the tip of one arm to the tip of the other well over 5 m. By contrast, Vitruvius gives his machine a *foramen* of 17½ digits (32.4cm), which results in springs only 2.82m high, and a machine whose overall size was a metre smaller than Philon's in length and width.

Artillery in the early Empire (Plate D)

The historian Josephus, writing about Rome's Jewish War (*Bellum Judaicum*) around AD 75, describes the artillery of the imperial legions in action. In AD 67, no fewer than 160 catapults were deployed, alongside archers and slingers, for the future emperor Vespasian's assault on Jotapata. These included arrow-firers shooting incendiary missiles, and massive 1-talent (26kg) stone-projectors. The latter perhaps belonged to Legion X *Fretensis*, which famously besieged Masada in AD 74. That legion's one-talent machines were apparently the largest *ballistae* at Jerusalem, during the siege of AD 70. Josephus claims that the huge white *ballista* balls had to be blackened, so that the defenders could not track their long approach and take evasive action.

During the civil war that brought Vespasian to the throne, his enemies deployed artillery for the night battle outside Cremona in AD 69. The writer Tacitus's story of how two soldiers managed to disable a large stone-projector is one of the last explicit references to the stone-



Catapult arrowheads with tangs for insertion into the arrow shaft are less common than the socketed variety. These examples from Qasr Ibrim (Egypt) date from the late 1st century BC; their length (c. 48mm tip) and weight (c. 15g) are not excessive, but their pyramidal points suggest artillery projectiles. It is presumed that the tang was fitted into a short, hardwood foreshaft, which was then attached to a longer shaft of soft wood. (© The British Museum)

Wooden foreshaft (*c.* 13cm) for a catapult arrow (Qasr Ibrim, Egypt). Wind tunnel tests indicate that, fitted with an arrowhead, this object would have performed well as a short crossbow quarrel. However, studying similar hardwood objects from Haltern (Germany), Schramm suggested that they were components of composite arrow-shafts. Fitted with a tanged arrowhead, the foreshaft could be slotted into a longer soft-wood shaft, just like the more familiar socketed arrowheads. (© The British Museum)

throwing *ballista*. But more graphical evidence of the battle comes from the archaeological remains. All eight washers and two front shields (one very fragmentary) from two arrow-firers were discovered in a pit near the battlefield, where they had perhaps been hidden by scavengers. The *foramina* of the washers indicate a 3-span machine and a larger one of around 2¾ft.

Roman artillery missiles

The distinctive socketed arrowheads with square-sectioned pyramidal points, like those discovered at Ephyra, are fairly common finds amongst Roman military equipment, and are usually considered to denote catapult missiles. Certainly, they are ideally suited to sliding along the groove of a catapult, and their aerodynamic properties make them perfect for high-velocity flight. Nevertheless, it has been noted that, far from automatically indicating artillery, such missile-heads could quite easily have come from lightweight spears and javelins.

If they are indeed to be interpreted as catapult missiles, the range of sizes represented ought to denote differences in calibre. It is thought that the head generally accounted for around $\frac{2}{15}$ of the entire missile, and the total length was, of course, directly related to the size of catapult. Thus, the 10cm arrowhead from Ephyra probably belonged to a 2½ft (77cm) arrow, which would have weighed around 200g. According to the old Greek formula, a stone-projector with an 8.5cm spring-diameter (the same as a 2½ft arrow-firer) used a much heavier missile of 290g; but the shorter springs of the arrow-firer stored only about 70 per cent of the energy stored by the stone-projector's springs, thus accounting for the lighter arrow.

Few collections of *ballista* balls from the Roman era have been studied. And, as with the pyramidal arrowheads, an alternative function has been suggested for boulders found on military sites; it is well known that the ancients often resorted to throwing rounded stones by hand, so we should be wary of interpreting every example as a *ballista* ball. Twenty stone balls were recovered from the site of Numantia, besieged by the Romans in 133 BC, and another 15 from the legionary fortress of Cáceres in Spain, which was probably occupied throughout the 80s BC. Half a dozen have come from Alesia, the scene of Caesar's siege in 52 BC, and the siege site of Burnswark in Scotland has produced 11, which may have been deposited at any time from the mid-2nd century AD to the early 3rd. In addition, isolated examples are common across the Empire.

Better evidence might be expected from the known siege sites of the Jewish War period (AD 66–74), several of which remained undisturbed until modern times. Certainly, Gamala, besieged by the Romans in AD 67, has produced over 2,000 *ballista* balls that cluster, surprisingly, around 3 or 4kg. By contrast, at Jotapata, taken by siege some months earlier, only a few dozen balls have come to light, none heavier than 2kg. And fieldwork at Machaerus, besieged in AD 71, turned up only 20-odd stone balls ranging in weight from 295g to 1.25kg, with single examples of 2.7, 4.0, and a massive 90kg. The hundreds of *ballista* balls reported at Masada by the excavator Yigael Yadin held out hope of a collection to compare with the earlier ones from Rhodes and Pergamon. However, only 50 of them, averaging 1–2kg, were subjected to detailed analysis; larger sizes ranging up to 26kg might have been expected. Finally, around 200 *ballista* balls were apparently recovered from the vicinity of Herod's palace in Jerusalem; it is thought that eight weight categories may be represented, from 0.5kg (roughly ½ *libra*) up to 26kg (80 *librae*), but details remain unavailable.

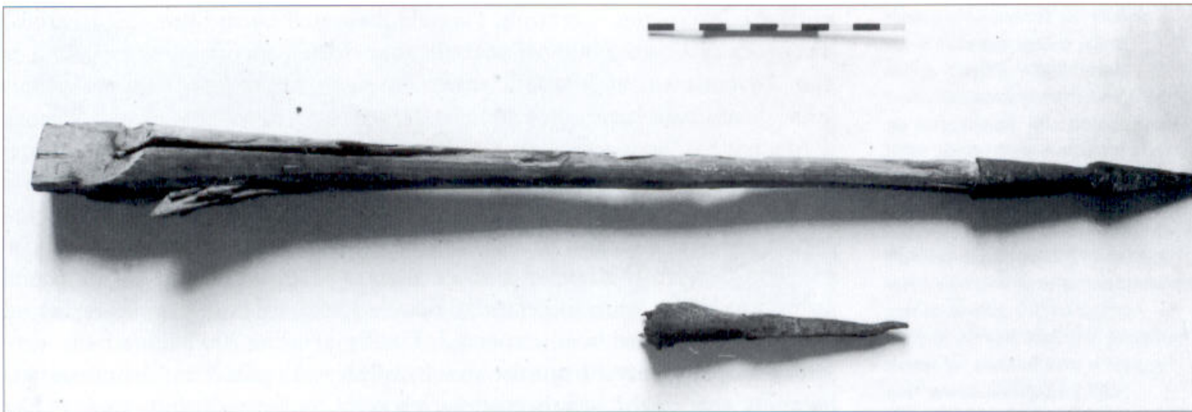
THE ROMAN ARTILLERY REVOLUTION

The iron-framed arrow-firer (Plate E)

It was long ago realised that the catapults depicted on Trajan's Column differed noticeably from those on earlier relief sculpture. The column's great spiral frieze depicts the events of Trajan's Dacian Wars (AD 101–2 and 105–6), and was sculpted during the period prior to its official dedication in AD 113. Thus the new design of catapult must have been introduced before that date.

Schramm believed that Trajan's catapults differed from earlier machines in only one respect, namely that the torsion-springs were apparently enclosed in weatherproof cylinders. But it was left to Marsden to elucidate the true nature of the redesign, which involved nothing less than the abandonment of the old euthytone design, last glimpsed on the Vedennius tombstone of the AD 80s or 90s. Henceforth, the arrow-firer

A scene from Trajan's Column (Rome), showing a catapult mounted in a two-wheeled cart. This is thought to be the *carroballista* mentioned by the late Roman writer Vegetius. It is not known precisely how the catapult was mounted in the cart, nor whether it was really intended to fire over the heads of the mules, as depicted here. Curiously, artillery was not widely used on the battlefield and mobility does not appear to have been a major concern. (C. Cichorius, *Die Reliefs der Traianssäule*, Berlin, 1900)



would have separate springs, like the palintone stone-projector, and it duly became known, somewhat confusingly, as a *ballista*.

The 460mm ash-wood *ballista* bolt from Dura Europos (Syria) tapers from a diameter of 30mm at the rear to 14mm where it enters the socketed iron head; the pyramidal point is 46mm long. The missile was designed for the new arrow-firing *ballista*, and has completely different proportions from earlier catapult arrows. Its tapering profile and armour-piercing tip make it a destructive weapon. (© Yale University Art Gallery)

Heron's *cheiroballistra*

The clue to the identity of the new arrow-firing *ballista* lies in a dark and difficult Greek text entitled 'Construction and dimensions of Heron's *cheiroballistra*'. Its dating is not certain, though scholars have generally been at pains to dissociate it from the 1st-century Heron of Alexandria. (The author is sometimes dubbed Pseudo-Heron to emphasise this.) The argument rests chiefly on the grounds that, as the machine only appears after AD 100, a Neronian engineer cannot have written about it, and it must be admitted that the chronology would be a little tight.

The importance of the text rests upon Marsden's realisation that the machine it describes, the *cheiroballistra* or 'hand *ballista*' (the Latin form, *manuballista*, is found elsewhere), closely resembles the artillery depicted on Trajan's Column. The text actually consists of a list of component parts with their dimensions, rather than proper assembly instructions. In summary, there is a stock, comprising the familiar pipe and slider, and incorporating a crescent-shaped fitting at the rear; a trigger mechanism, fitted to the slider; a pair of frames called *kambestria* (Marsden's 'field-frames'); four washers with levers; two struts, one arched (*kamarion*) and one laddered (*klimakion*); and two bow-arms.

Marsden realised that each *kambestrion*, comprising two iron rings held apart by two iron posts, was intended to hold a torsion-spring, just like the individual springs of the palintone stone-projector. (Like Schramm, he enclosed each spring in a thin metal cylinder, but the sculptural evidence of Trajan's Column is ambiguous on this point.) Marsden further reasoned that the two struts, the *kamarion* and *klimakion*, took the place of the wooden framework of the stone-projector, and were intended to link the two *kambestria*. In fact, the struts each terminate in a pair of brackets, whose forked ends are the same distance apart as the iron uprights of the *kambestria*. Marsden cleverly drew the conclusion that these brackets were intended to grip the 'field-frames' at the top and bottom, and hold them in place.

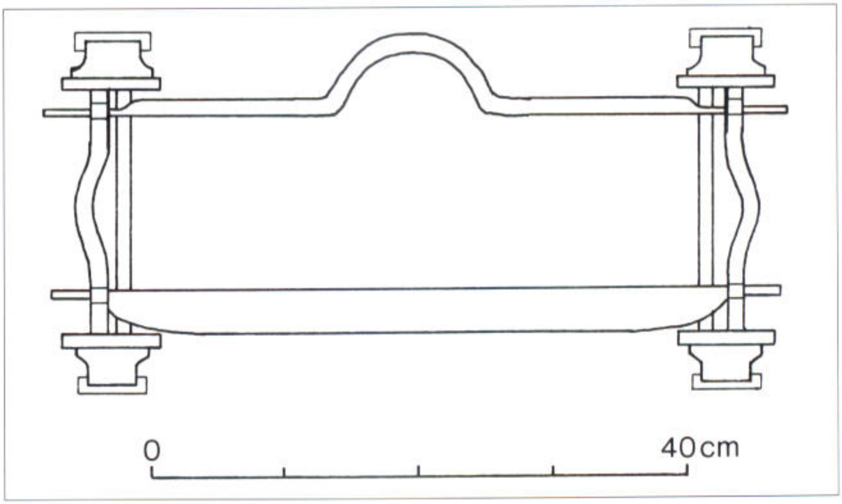
All of the components are reasonably easily deciphered, at least with the benefit of Marsden's analysis, yet the design of the *cheiroballistra* remains controversial. A strict reading of the text results in a very small machine, as befits a hand weapon. For example, the stock measures roughly one metre in length; the field-frames, 20.6cm high (11⅙ daktyls) with a 3.7cm (2 daktyls) spring-hole, are set 43.5cm (1ft. 7½ daktyls) apart; the bow-arms are only 20.4cm long (11 daktyls); and the washers have a tiny spring-diameter of 2.5cm (1⅓ daktyls).

Although no components matching the dimensions in the text have ever been found, small torsion-powered hand weapons are known to have existed in the ancient world. The type 6 washer from Ephyra has an inner diameter of 3.4cm; two slightly larger examples have been discovered in Britain, one from Elginhaugh (3.5cm) and the other from Bath (4.0cm); and two late Roman examples were found at Volubilis in Morocco (4.1 and 4.4cm). Nevertheless, successive commentators have tried to enlarge various components to make a full-sized catapult, although it seems obvious that the *cheiroballistra* was a hand-held weapon. In particular, the crescent-shaped fitting at the rear of the stock served the same purpose as the stomach-rest of the old *gastraphetēs*.

The design of the arrow-firing *ballista*: the field-frames

Marsden did not live to see the archaeological confirmation of his conjectures. In fact, over the last 30 years, largely due to the efforts of the German scholar Dietwulf Baatz, parts from iron-framed catapults have gradually come to light from several late-Roman sites. Unfortunately, none exactly matches the minuscule dimensions of the *cheiroballistra*, but the same basic design can be discerned, enlarged into a full-size catapult.

Compared with the *cheiroballistra*, the three *kambestria* found at Gornea (Romania) are shorter (13.3, 14.4, 14.6cm), but have wider spring-holes (5.4, 5.9, 5.4cm); the single *kambestrion* from Lyon (France) is much taller (32.5cm) and wider (spring-hole approx. 9cm); the one from Orşova (Romania) is even taller (36cm) but narrower (spring-hole 7.9cm); and the one from Sala (Morocco) is taller still (37.4cm; spring-hole 8cm). It seems that, whereas the old-style catapults maintained a basic relationship between spring-height and diameter, the same cannot be said for the new-style iron-framed machines.



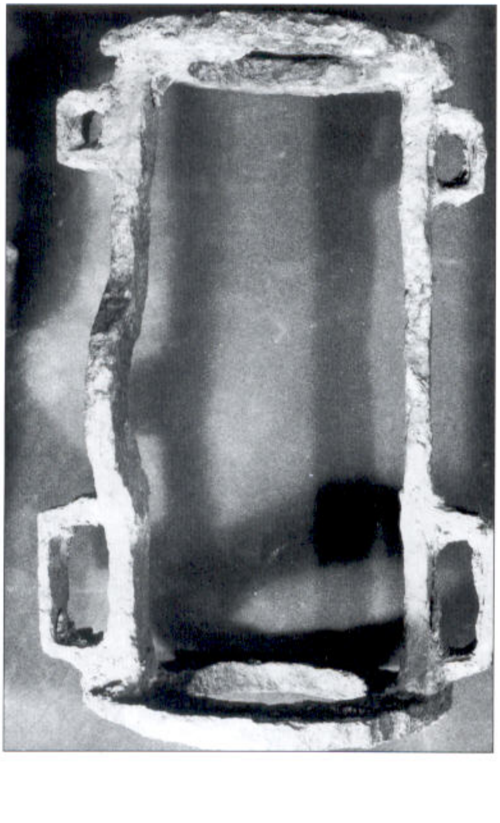
The spring-frame of Heron's *cheiroballistra*, following the dimensions in the text. It is often stated that the washers (inner diameter 25mm) are too small for an effective weapon, and several scholars have made amendments to the text in order to create a larger machine. (Author's drawing)

Of course, the *kambestrion* does not tell the whole story. The washers, sitting at either end, increased the overall spring-height and determined the spring-diameter. It must be remembered that the old-style *ballista*'s spring-hole was recessed to receive the washer, and consequently had the same spring-diameter; by contrast, the new-style *ballista*'s washer sat within the *kambestrion*'s spring-hole, with the result that the spring-diameter was smaller than the spring-hole. This is best illustrated by the Lyon *kambestrion*, which still has its original washers: the spring-hole is roughly 9cm in diameter, but the inner diameter of the washers (and hence the spring-diameter) is only 7.5cm. Furthermore, the washers are roughly 6cm high, making the total spring height 44.5cm, equivalent to almost six spring-diameters. By contrast, the *cheiroballistra* washers sit 2.9cm (1 7/12 daktyls) above the *kambestrion*, giving a spring-height of 26.4cm, which is more than ten spring-diameters.

The design of the arrow-firing *ballista*: the spring-frame

Several individual washers are known from late contexts, but they tell us little without their associated *kambestria*. A different association exists at Orşova, where the *kambestrion* was found with a *kamarion*, the long arched strut that connected the tops of the field-frames. Again, this component is far larger than the one in Heron's *cheiroballistra* text. The strut has suffered damage at both ends, but enough survives to confirm that the forks of each bracket were about 18cm apart. As the *kambestrion* is 17.5cm wide, and could comfortably be gripped by the *kamarion*, it seems fairly likely that the two components belong together.

The Orşova combination produces a very low frame, with a width-to-height ratio of more than 3:1, whereas the one described in the *cheiroballistra* text is only 2:1. Did a different set of proportions apply to the stand-mounted version of the machine? Marsden had decided to double the height of the *cheiroballistra* field-frames, in the belief that the machine's proportions should resemble those of its Vitruvian predecessors as far as possible. However, Baatz largely restored the original dimensions, and explained the wide frame as an aid to observing potential targets. In addition, it solved



The *kambestrion* ('field frame') discovered at Lyon (France) may well date from the battle between Emperor Septimius Severus and the pretender Clodius Albinus in AD 197. Apart from the associated washers and levers, no other catapult parts survived. The upper and lower struts of the spring-frame would have slotted into the crudely made brackets projecting from either side of the *kambestrion*, and were perhaps wedged in place. (© Musée de la civilisation gallo-romaine, Lyon)

a serious problem of the Vitruvian design, namely the possibility of the arrow ricocheting off the wooden uprights during its passage through the narrow gap (*dioptra*) in the spring-frame.

The stone-projecting *ballista* (Plate F)

It is usually assumed that the stone-projecting *ballista* continued in operation, although Tacitus, writing around AD 100, is the last to mention it by name. No stone-projectors appear on Trajan's Column, and the Hadrianic writer Arrian simply calls his stone-projectors 'machines' (*mēchanai*).

The remains of a medium-sized catapult found in the ruins of Hatra (Iraq) have been hailed as evidence of the stone-projecting *ballista* in the early 3rd century AD. However, the discovery has presented scholars with something of a puzzle. Only the 2mm-thick bronze plating for the spring-frame survived, where the catapult had toppled forwards onto the ground (see drawing on p.45); the wooden stock and stand had long since disappeared, but three of the four washers survived. These were of such robust construction that, when he studied the finds in 1975, Baatz considered them to have come from a medium-sized stone-projector. He duly reconstructed the machine, albeit tentatively, as a variant form of Vitruvius's 10-pound *ballista*.

Baatz noted the wide-set springs and the unusually squat frame. However, the semicircular cut-outs on the side uprights defied all explanation at the time. Although similar to the cut-outs in the Vitruvian *ballista*, they are clearly in the wrong place, facing inwards instead of backwards. But, if their purpose is the same – namely, to provide free space so that the arms do not hit the wooden upright – then it would seem that the arms of the Hatra *ballista* were arranged in a different manner from those of the Vitruvian *ballista*. In fact, the peculiar design of spring-frame only makes sense with interior-swinging arms.

The idea of interior-swinging arms is not a new one, but it has never achieved wide acceptance, no doubt owing to the lack of a full-size replica to demonstrate the practicalities. The action, though unfamiliar, is straightforward. When at rest, the arms project forwards. On spanning, they are drawn back through the wide empty frame; in the process they travel through an arc approximately twice

For his reconstruction of an iron-framed *ballista*, Alan Wilkins used the proportions of the *cheiroballistra* spring-frame; but he increased the machine's power by almost doubling the washers' inner diameter to 4.9cm and lengthening the bow-arms to 33.7cm. The resulting machine can punch a hole in 2mm sheet steel from a distance of 50m, using a replica of the Dura bolt. (© A. Wilkins)

as long as the Vitruvian palintone, storing double the energy. On release, the arms spring forward until stopped by the bowstring; as in earlier palintones, the arms do not hit the frame uprights, but swing into the free space created by the cut-outs.

The Spanish scholar Aitor Iriarte has observed that the cut-outs perfectly echo the same feature on the iron-framed *ballista*, which may suggest that these, too, had interior-swinging arms. This is certainly the opinion of the British scholar Michael Lewis, who has even questioned the identification of the Hatra machine as a stone-projector, suggesting that it was in fact a heavy-duty arrow-firer. Clearly, there remains much work to be done in studying later Roman artillery.

The *kamarion* ('arched strut') from Orşova (Romania). This is from a much larger machine than the one described in the *cheiroballistra* text, where this component's main stretch measures only 43.5cm (1ft 7½ dactyls), not including the forked bracket at each end. By contrast, the corresponding stretch on the Orşova example is a massive 1.25m. (© D. Baatz)

The stone-projecting *onager* (Plate G)

The soldier and writer Ammianus Marcellinus is a particularly valuable source, as he witnessed many momentous events in the third quarter of the 4th century AD. In a well-known digression, he attempts to describe the siege-machinery and artillery of his own day, with varying success; although his description of the *ballista* is incomprehensible, his remarks on the one-armed stone-projector are fairly clear (though still vague enough to have spawned three different reconstructions).

In short, a single torsion-spring was mounted transversely in a recumbent timber frame. A single, wooden arm was slotted into the spring halfway along, so that it stood upright and travelled in a vertical arc; a sling attached to its free end released a stone when the arm reached the top of the arc. Ammianus claims that the machine was called the *onager*, or wild ass, because it kicked up stones; previously, it had been known as the *scorpio* (scorpion), no doubt because of the resemblance between the upright arm and the scorpion's tail. (It is clear that, across the centuries, artillery terminology gradually changed, for in Vitruvius's day the *scorpio* was a light-calibre arrow-firer.)

In the absence of a bow-string, which arrested the arm movement in the traditional two-armed catapult, this machine required a padded buffer to stop the arm. Ammianus writes that, 'in front of the wooden structure [the *onager*], a huge buffer is spread out: namely, a sack stuffed with fine chaff, secured with strong binding, and located on heaped up turves or piles of bricks.' Marsden was misled by the philologist Rudolf Schneider into believing that the entire machine sat on a pile of turf or bricks; it seems, however, that Ammianus meant the buffer alone was raised up in this way. This perhaps applied only to the larger machines, such as the one that famously misfired at Maozamalcha in AD 363, crushing the chief artilleryman with its stone.

A turf buffer would have been a liability whenever the *onager* had to be moved. Yet, Ammianus mentions no such upheaval in connection with the nocturnal redeployment of four machines at Amida in AD 359. In fact, for lighter models, the design proposed by Napoleon III's general, Verchère de Reffye, would have been quite suitable; by incorporating a separate timber-framed buffer, this design reduced the overall weight of the *onager* and increased its manoeuvrability.

In practical tests using miniature models, Michael Lewis demonstrated the superiority of a forward-sloping buffer over the more familiar vertical one. He was also able to establish that the length of the sling had a real bearing on the range of the missile, and that, far from simply lobbing stones in a high arc, the sling could be set to release its missile in a flat, direct trajectory. Modern commentators often assume that the *onager* represented a decline in ancient artillery, but they are confusing simplicity with clumsiness. In fact, it seems to have been an efficient and easily operated machine, and the single torsion-spring removed the need, intrinsic to two-armed catapults, for fine-tuning and balancing a pair of springs.

CONCLUSION

A number of uncertainties still surround the subject of ancient artillery, and a new generation of scholars is currently at work to solve them, but the broad outlines are fairly clear. In 1930, Sir William Tarn felt justified in writing that 'no improvements, except in details, were ever made upon the catapults of Demetrius' time', and as recently as 1972 one critic could claim that, 'under the Romans, there were few genuine improvements in construction and efficiency'. On the contrary, it is clear that the catapult continued to develop and improve in its various forms, from the 4th century BC right up to the 4th century AD.

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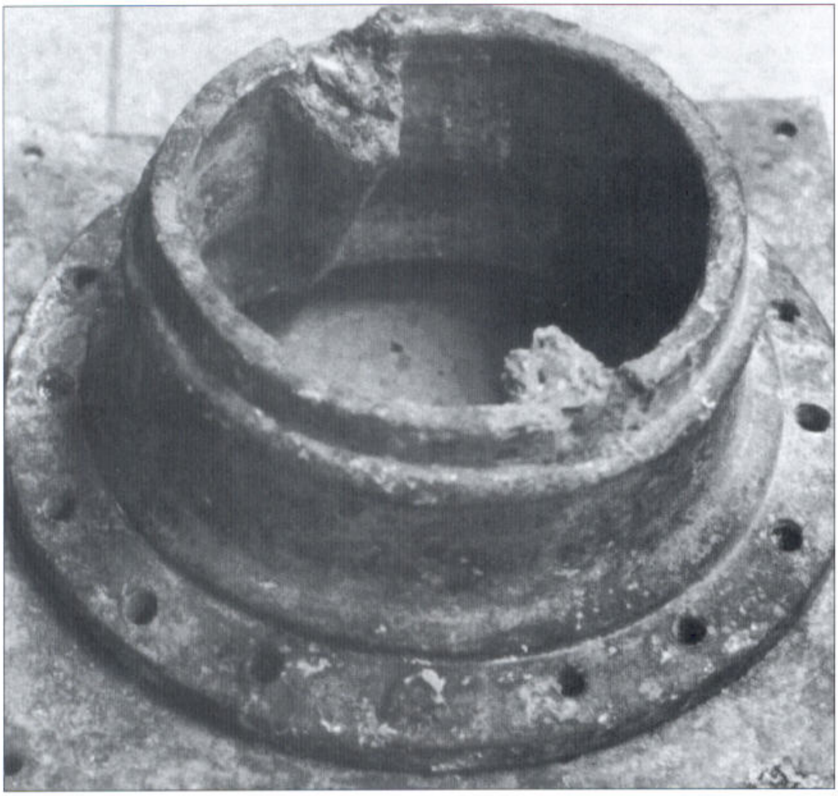
The artillery-related works of Biton, Philon, Heron, Vitruvius and Ammianus have been translated into English by E. W. Marsden. Less accessible, but no less authoritative, are the earlier translations into German by E. Schramm (in collaboration with the philologist H. Diels). In the French tradition of Vitruvian scholarship, L. Callebat and P. Fleury have studied Vitruvius's chapters on artillery in their edition of the tenth book of the *De architectura*. Readers should be aware that many technicalities in these ancient texts are still fiercely disputed.

Heron's *cheiroballistra* continues to provoke controversy. Building upon Marsden's work, Alan Wilkins has developed his own interpretation of the



One of the washers belonging to the Hatra ***ballista***, complete with counter-plate. The washer (inner diameter 16cm) has 16 locking holes around the flange, while the counter-plate has eight. Notable features of the washer are the reinforcing ribs beneath the position of the lever, where considerable pressure could be expected. (© D. Baatz)

text, contested by Aitor Iriarte in several respects. Michael Lewis's interesting ideas regarding this machine have yet to see publication, but his version of the *onager* (in collaboration with the mathematician V. Hart) is persuasive. Finally, the serious student of artillery cannot ignore the work of Dietwulf Baatz, who has been instrumental in elucidating the physical remains of catapults, and whose work encompasses much more.

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COLOUR PLATE COMMENTARY

A. EARLY BOW-MACHINES

By the early years of the 4th century BC, several variations of the *gastraphetēs* were probably already known. They were powered by large composite bows, which consisted of a wooden core sandwiched between a layer of horn and a layer of sinew. When the bow was bent, prior to firing the shot, the sinew along the back (the side of the bow facing away from the archer) stretched, while the horn along the belly (facing the archer) was compressed; on release, each element snapped back to its original state, powerfully propelling the arrow forwards.

Besides the original hand-held *gastraphetēs*, the machines shown are the 'mountain' version, presumably for use over rugged terrain, and the twin-bore version, both created by Zopyrus. The description of Biton, a later writer based in Pergamon, has been followed closely to give an alternative reconstruction to those of Schramm and Marsden.

B. THE FORTIFIED FARMSTEAD AT EPHYRA

The fortified Greek farmstead at Ephyra produced finds of agricultural and woodworking tools, and the six ground-floor storage rooms were filled with jars of beans and cereals. However, the most striking finds were the 21 catapult washers and 27 iron missile-heads that must have fallen from an upper storey when the Romans destroyed the place in 167 BC.

The machine shown here is the largest of the Ephyra catapults: a 4ft arrow-firer, designed to shoot a missile 1.22m long. The shallow profile of the bronze washers suggests a fairly early date, perhaps around 225 BC, and the machine has been reconstructed according to the instructions of Philon.

C. THE 3-TALENT STONE-PROJECTOR OF DEMETRIUS POLIORCETES

Diodorus claims that, when Demetrius besieged Salamis (Cyprus) in 307 BC, his 40m siege-tower contained stone-projectors in the lower storeys. The largest of these were apparently 3-talent machines. Based on a spring-diameter of 56cm, these rare machines must have been enormous. Mathematical calculation suggests that they could reach 180m with a direct shot, corroborating a similar claim made by a later Roman author named Athenaeus.

The constructional details of the stone-projector's spring-frame were worked out by Schramm, but the stand remains conjectural. Such a bulky machine cannot have been manoeuvrable and will have had no need of a tilt-and-swivel base. The massive weight of the pull-back system probably required triple-haul pulley blocks, and the winch has been extended to allow a crew of nine to operate it. Just how the crew got the 78kg stone balls onto the machine's slider remains a mystery.

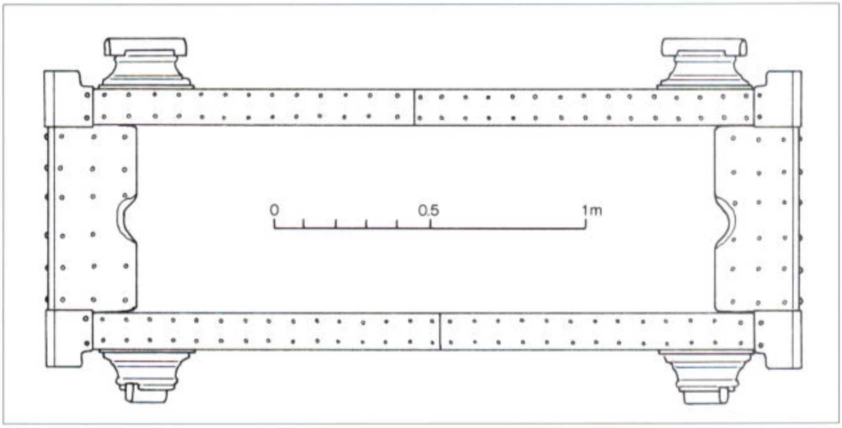
D. ROMAN ARTILLERY, *c.* AD 69

In October AD 69, Roman forces drew up artillery along the road at Cremona to halt the advance of a rival army. The historian Tacitus mentions a large stone-projecting *ballista*, and archaeological remains of arrow-firing *catapultae* have been found in the neighbourhood.

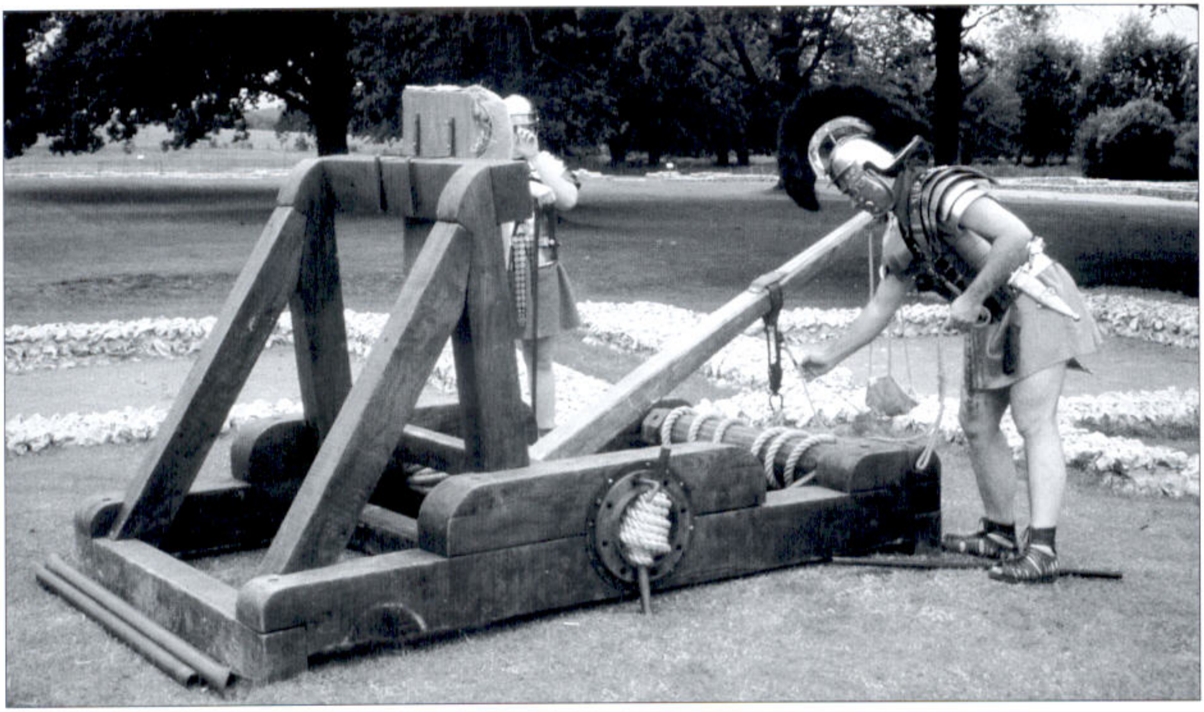
The machines depicted here follow the descriptions of Vitruvius as far as possible. The *ballista* is a medium-heavy 40-pounder with 24cm-diameter springs. Some details remain controversial, such as Vitruvius's omission of the long, diagonal support struts that Heron mentions. Likewise, the arrow-firers follow Vitruvius's description and differ from earlier models in their taller springs and curved bow-arms. The reconstruction incorporates the archaeological evidence of washers and front-plates found at the site.

E. THE NEW-STYLE ROMAN ARROW-FIRER

The iron-framed *ballista* first appears on Trajan's Column, where one scene depicts the machine on a timber platform and surrounded by a timber construction. It is thought that this scene represents a response to the vulnerability of artillery-crews. Housing the *ballista* in a protected emplacement would have provided the twin necessities of a firm base for the machine, and a shelter from the elements as well as from enemy fire. Although the late writer Vegetius claims that each machine was served by a crew of 11, the Trajan's Column scene depicts only two men, probably representing a gunner and a loader. The machine is based on a scaled-up version of the *cheiroballistra*, incorporating dimensions from the Lyon torsion-spring. The stand and winch are conjectural.

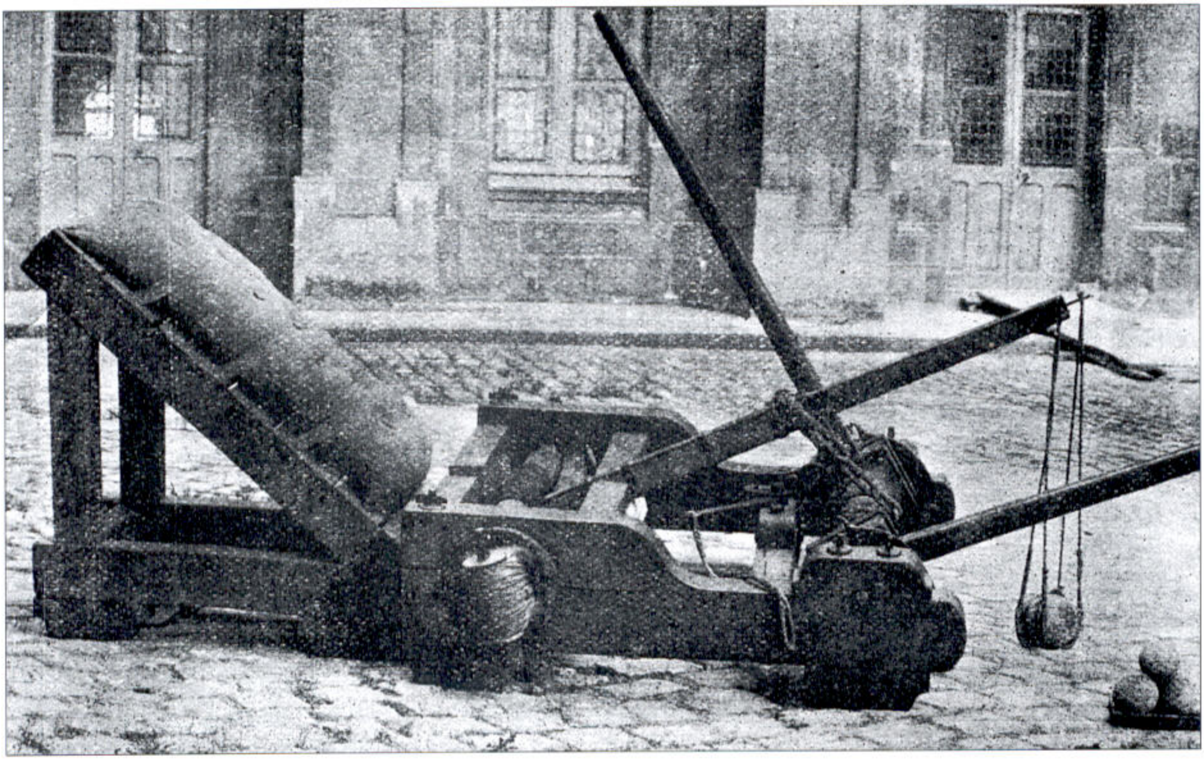


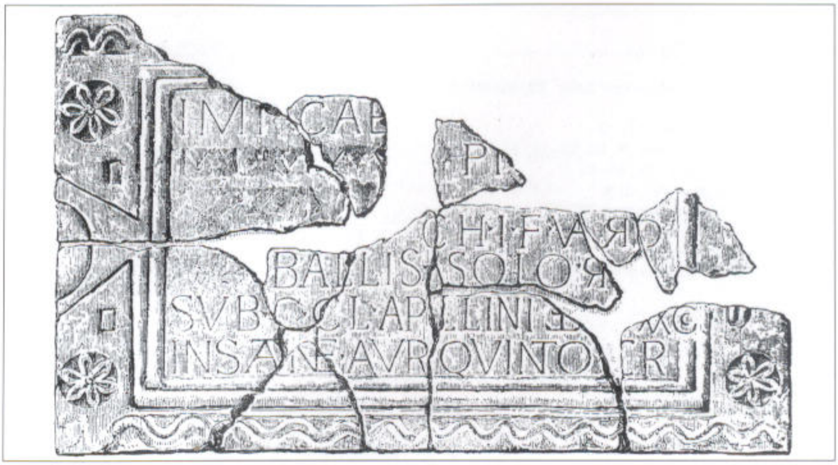
The shape of the Hatra *ballista*'s spring-frame is preserved by the 2mm-thick bronze sheeting which originally covered it, and the unique corner-pieces. All four washers are shown in their original positions. (Author's drawing)



ABOVE **The Ermine Street Guard's reconstruction of a small *onager* follows the design proposed by Sir Ralph Payne-Gallwey. The machine is only fired in demonstrations using wooden missiles, so its potential has never been tested. (© Ermine Street Guard)**

BELOW **The *onager* built by Verchère de Reffye, one of Napoleon III's generals, illustrates the most efficient design for this machine. The arm incorporated an adjustable pin, onto which the sling was fastened; this would have enabled variations in missile trajectory. (Author's collection)**





Inscription from High Rochester (Northumberland), recording repair work to a 'ballis(tarium)' around AD 235. For a long time scholars interpreted this as an 'artillery platform', but it was probably a storehouse or workshop for catapults. Whenever needed, the machines would have been deployed under cover in tower chambers. (J. C. Bruce, *Lapidarium Septentrionale*, London, 1875)

F. THE HATRA *BALLISTA*, *c.* AD 200

Only the bronze cladding of the spring-frame, along with a unique set of eight cast bronze corner fittings, remain from the Hatra *ballista*, along with four counter-plates and three of the four washers. There is no evidence to suggest what the rest of the machine looked like, although it must have been a large catapult and, as such, would have sat on a firm timber stand.

The size of the washers, by far the largest ever found, and their robust construction, have led to the suggestion that the machine was a stone-projector, albeit a lightweight one (*c.* 3.5kg). The wide-set springs and empty frame can have had no other purpose than to allow interior-swinging arms, an arrangement which has certain implications for the design of the stock. For example, the forward swing of the arms requires that the stock must project well beyond the front of the spring-frame, in order to support the slider while the trigger catches the bowstring.

G. THE *ONAGER*

Although there are hints that it existed earlier, the *onager* is first described in AD 359 by Ammianus Marcellinus. Like other catapults, it would have come in various sizes, and smaller versions would have been easily transported by gangs of artillerymen. Again, like earlier stone-projectors, they could be equally as effective against enemy siege-machinery as against personnel; stones fired by *onagri* at Amida are said to have crushed enemy heads.

The machine depicted here is based around a 50cm-thick torsion-spring, which ought to be sufficiently powerful to fire stone balls weighing 1 talent (26kg). The arm will have hit the buffer with considerable force, and the turf banking was designed to absorb the impact. It was perhaps a machine of this size that Ammianus was describing when he said it required eight strong men to winch down the arm; the Ermine Street Guard's *onager*, by contrast, can be winched by two men. Ammianus's description is fairly vague, so many of the details remain conjectural.

A scene from Trajan's Column (Rome), showing an iron-framed *ballista* mounted on a timber platform. Unlike artillery of the gunpowder age, catapults produce no noticeable recoil, as there was no explosive charge. The supposition that heavier catapults had to be sited on a resilient platform is a popular misconception. (C. Cichorius, *Die Reliefs der Traianssäule*, Berlin, 1900)

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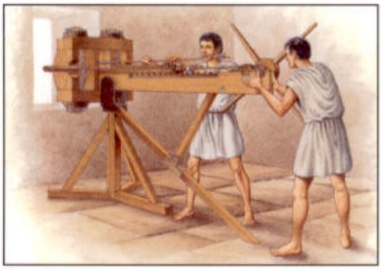

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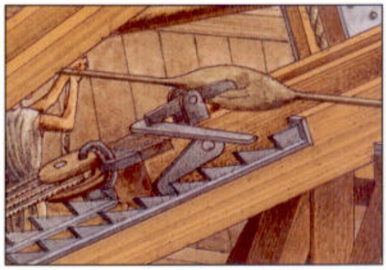

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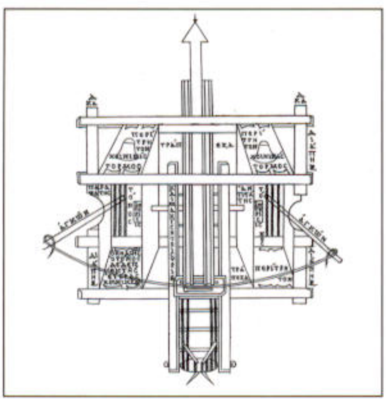

Plans

Photographs

Greek and Roman Artillery 399 BC–AD 363

The catapult (*katapeltikon*) was invented under the patronage of Dionysius I, tyrant of Syracuse, in the 4th century BC. At first only the arrow-firing variant was used, and it was not until the reign of Alexander the Great that stone-projecting catapults were introduced. The Romans adopted these weapons during the Punic Wars and further developed them, before introducing the new arrow-firing *ballista* and stone-throwing *onager*. This title traces the often controversial design, development and construction of these weapons throughout the history of the classical world.

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