A suggested reconstruction of Vitruvius' Stone-thrower: *de Architectura* X, 11, 4 - 9

Alan Wilkins

With a full-size 2 *librae* version constructed by Len Morgan

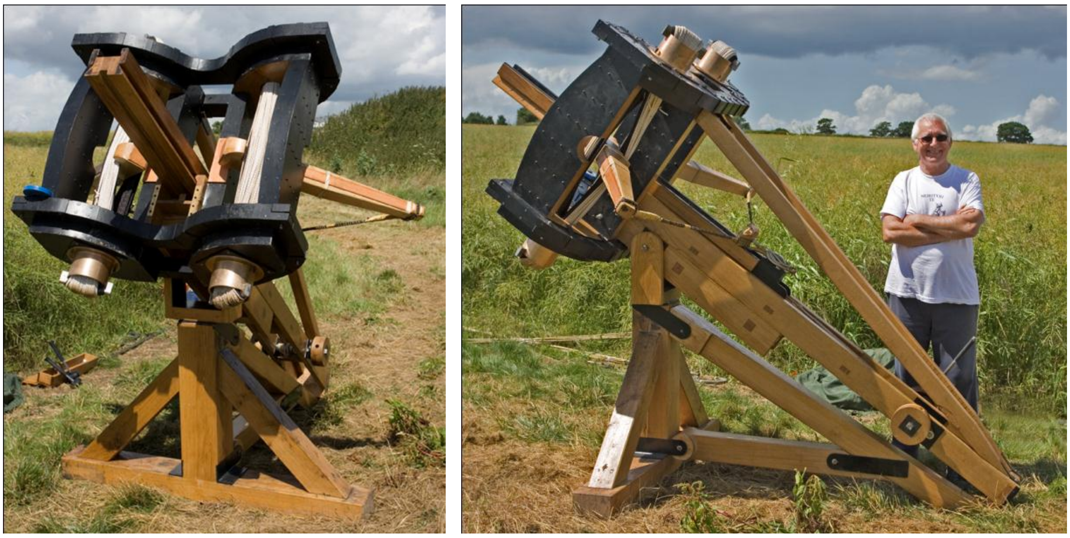


Figure 1: Len Morgan with the Mk I 2 *librae* Vitruvian *ballista*, based on the writer's interpretation of the evidence and model, and modifications resulting from Len's experience of building at full-size. The Mk II version to be tested in September 2011 incorporates further adjustments, including a revised design of bowstring.

INTRODUCTION

The *ballista*, the stone-throwing catapult described by Augustus' artillery engineer Vitruvius, is a far more complex machine than the bolt-shooting *catapulta*. All attempts to reconstruct the latter are now able to make use of the exciting evidence of parts of three front frames discovered at Ampurias, Caminreal and Xanten. Unfortunately no finds of parts from the Vitruvian *ballista* have been identified to date. The catapult has to be reconstructed from the Latin text of Vitruvius and the description in Greek by Philon of an earlier version of the machine; both engineers give details of parts and their dimensions. The Greek text of the third engineer, Heron of Alexandria, does not list sizes, but offers highly valuable information about the functioning of individual parts, problems that may be encountered, etc.. Furthermore Heron's diagrams have survived in the manuscripts, whereas those that originally accompanied Vitruvius' and Philon's texts are lost.

It might seem unsafe to attempt to reconstruct this complex machine solely from verbal descriptions in copies of manuscripts where accompanying diagrams are missing and parts of the text and the numerals recording sizes have become corrupt. However the *ballista* and *catapulta* had developed as siblings throughout their history, designed by the same engineers and built in the same workshops. So the principles of the bolt-shooter's construction, using hefty hardwood frames reinforced by metal plating secured by large rivets, applied to the stone-thrower. Modern reconstructors of Roman stone-throwers can therefore utilise the mass of information afforded by the metal framework of the Ampurias and Caminreal bolt-shooters, and the remarkable survival of both the wood and the metal plating of the Xanten find.

Reliance on Vitruvius' text in the surviving manuscripts is fraught with problems. They are of course all hand copies; the earliest and best one, Harleian 2767 in the British Library, was written c. AD 700 by monks in the very same writing room (*scriptorium*) as the Lindisfarne Gospels, seven centuries after Vitruvius handed his master copy to his publisher in Rome. Hand-copied mss can be traced back like human family trees; and just as a faulty gene may be inherited, so when a copy of a book is flawed, either because of a copyist's mistake or by physical damage, all copies descending from that one will be liable to repeat the flaw. There are clear signs that Vitruvius' text has suffered badly in transmission. No diagram has survived; Harleian 2767 has blank pages for lost diagrams. Confusions have arisen because Vitruvius' text uses both words and Roman capital letters for cardinal numerals. It is easy to forgive the mistakes made by copyists. Some errors may have crept in when Vitruvius' text in Roman capital letters was transcribed into Uncial script around the 5th century AD. There are some possible gaps in the mss where parts of his text may have been lost; there is one item which has lost its name; a sentence describing the Washer-hole and Bar is out of position.

A typical passage giving the length and width of a part would originally have been written LONGITUDOFORAMINISSLATITUDOFORAMINISIS "*a length of half a spring-hole, a width of one and a half*". Both letter-numerals, S for a half, IS for one and a half, look the same as the end letter(s) of FORAMINIS "*of a hole*". Most Latin manuscripts leave no or very small gaps between words.

Numerals like VIII or XIIII can easily lose digits. The monks were not engineers and would not have fully understood the numerals they were copying. For fractions, engineers like Vitruvius used the first letters of the Greek alphabet. Even if the copyist did know the Greek alphabet, he would probably be ignorant of the digamma *F*, long obsolete in literature, which can be mistaken for a Latin F or E, or a Greek gamma Γ. Greek and Roman engineers continued to use the digamma for the numeral 6 and the fraction 6/16. The very first numeral in the description of the *ballista* has been corrupted to the word VEL meaning 'or' in Latin. The two strokes of the V may have been miscopied from the two-stroke numeral II, and the E could originally have been *F*, digamma. The L can be explained as accidental repetition (dittography) of the first letter of the following word. This is the type of textual detective approach required to produce possible answers to what Vitruvius originally wrote. The resulting measurement, two and six sixteenths, makes good sense in the context and unravels the rhombus figure described in the difficult Latin of Vitruvius' opening paragraph.

The combined result of the difficulties posed by the lack of any *ballista* finds, and by the problems in understanding the technical texts, with their missing drawings and manuscripts' defects, makes it hardly surprising that the earliest serious attempt to reconstruct a *ballista*, by Reffye and Dufour backed by Napoleon III, was so way off the mark that years later Erwin Schramm dismissed it as a product of Reffye's wild imagination and Dufour's failure to understand the Greek texts. This withering criticism was one of the many salvoes fired in what could be labelled as the Franco-German Catapult War. However, Schramm's verdict is arguably correct, and he had the right to deliver it because his own fine reconstructions were based on sustained, determined attempts to understand and interpret the Greek and Latin texts. To this end he enlisted the aid of the distinguished classical scholars Schneider, Diels and

Rehm, who collaborated with him in publishing a series of articles from 1904 to 1928. Many of Schramm's famous machines from his 30 year campaign of reconstruction survive in the museum at the Saalburg. A few were destroyed in the Second World War, including his *ballista*.

His article on Vitruvius' artillery, published in 1917 in collaboration with Hermann Diels, contains his version of the Latin text plus a commentary and small-scale interpretive plans. It has to be said that his edition of the Latin text is not entirely reliable: Eric Marsden spotted that Schramm has included "a number of items that would never seem to have been in Vitruvius' text" (Marsden 1971, 198 and further comment on 200). In dealing with the problems of the 49 numerals giving the sizes of *ballista* parts, Schramm has without explanation changed 20 to a reading quite unlike that written in the surviving copies. In almost all the 20 cases the existing mss readings make sense without requiring amendment. To be fair, because of the failure of his predecessors' attempts Schramm was starting from scratch in trying to understand the machine. Marsden (1971, 194) also rightly acknowledges, as everyone must, "the great debt which I owe to Schramm's edition…".

The following commentary is based on Vitruvius' list of parts (from Book X of his *De architectura*, published c. 25 BC). All quotations and figures in red are from him. Where appropriate, the information from the two Greek artillery engineers Philon (probably late 3rd century BC) in blue, and Heron (second half of the 1st century AD) in green, have been used to supplement Vitruvius' comments; such quotations are followed by (Ph.) or (H.). Their Greek treatises are both entitled *Belopoiika*, "Artillery Construction", and are translated in full in Dr Eric Marsden's masterly *Greek and Roman Artillery; Technical Treatises* (Oxford 1971, reprinted 1999 by Sandpiper). I have only occasionally revised his translations.

For the following text and translation I have consulted a photocopy of the Harleian 2767 ms, and the variant readings in the other mss recorded by the Teubner Edition editors Rose (1899) and Krohn (1912).

The engineers give all dimensions in spring-hole diameters, i.e. the diameter of the holes through which the skeins of sinew-rope passed, abbreviated to **h.** in the translation.

The following letters or signs are used for numerals in the surviving copies of Vitruvius

SYMBOLS FOR FRACTIONS IN THE MSS OF VITRUVIUS

3/16	Γ				
1/4	δ	9	÷	C	
5/16	ε	E			
6/16	*F*	ς	*Ɠ*	(digamma)	
7/16	ζ	Z			
1/2	S	CC	99		
9/16	Γ *F*	γ ς	Γ*Ɠ*		
10/16	Γ Z	γ ζ			
11/16	S				
3/4	S ÷	S 9	CCC	**.**VIIII (= 9/12)	
14/16	S *F*				

In a vain attempt to indicate the authenticity/reliability of the numerals in the following text - which ones are left alone as found in the mss, and which have been modified by modern editors - the following signs are used in the translation and the commentary:

19(Ph.) = information from Philon's list of measurements

19* = slightly corrupt manuscript numeral readily restored by standard textual criticism procedures

19** = corrupt numeral: less easy to restore

19*** = manuscript reading very corrupt: numeral estimated by modern editors

19# = numeral calculable from other dimensions

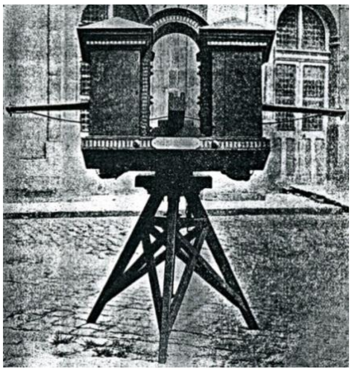
< > brackets mark word(s) supplied to fill a gap in the mss where Vitruvius' word(s) seem to have been lost.

[ ] brackets indicate modern remarks added to clarify / explain Vitruvius' text.

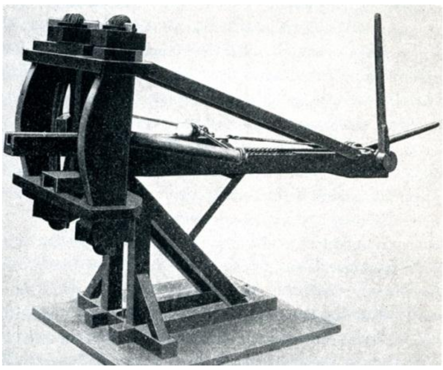
Everyone who attempts to reconstruct Greek and Roman artillery stands on the shoulders of a long line of those who have previously persevered to edit and make sense of the difficult Greek and Latin texts, and to relate them to the archaeological finds. In the case of the Vitruvian *ballista*, the contributions of Erwin Schramm (with Hermann Diels) and Eric Marsden are absolutely vital. Eric's untimely death prevented him from undertaking his intended programme of producing fresh reconstructions of all the catapults and a revised edition of his *Greek and Roman Artillery*. These are a tremendous loss. I have tried to maintain the momentum of his research, and am extremely grateful to Mrs Margaret Marsden and her family for help and encouragement in this.

Unfortunately the situation is no better now than in Schramm's day, in that no parts of a *ballista* of Vitruvian type have been identified. Therefore this article can only attempt to advance understanding of the machine by offering a new edition of Vitruvius' text and resulting interpretation of his *ballista*. I have given a lot of information about our reconstruction, but not full working drawings: neither Len nor I will supply these. We are extremely concerned about the dangers involved in building ancient catapults, and above all in operating them safely in public. There have been some serious accidents and one near fatal incident. ***caveat reconstructor*** !

I would like to pay tribute, as always, to the great technical expertise of engineer Len Morgan, and to his long labours in bringing this machine back to life. The series of Roman catapults that we have produced together over the last 15 years has been constructed by him to the highest standards - well up to those set by Erwin Schramm's team of technicians. We were joined several years ago by another skilled engineer, Tom Feeley, who has collaborated on the Vitruvian Three-span *scorpio*, the *cheiroballistra*, and the Xanten Two-span *scorpio*. He is currently completing, with



Reffye and Dufour's *ballista* (Clephan, 1903, Fig. 4)



Schramm's *palintonon* (Schramm, 1918/1980, Abb.21)

Len's support, a larger version of the metal-framed *cheiroballistra* which we believe to be that used for the *carroballistae* (figure 29a).

COMPONENTS OF THE SPRING FRAMEWORK

1. THE HALF-SPRINGS

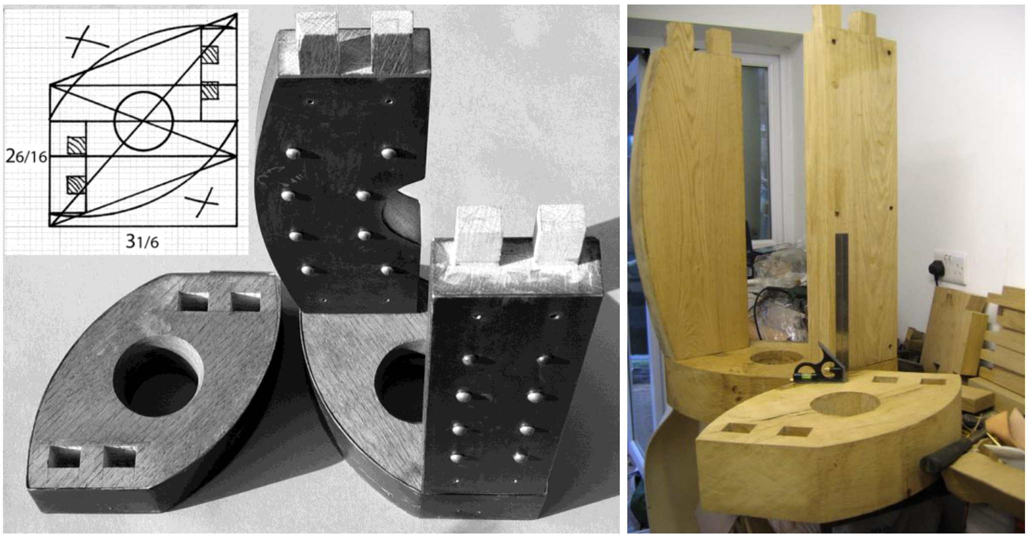


Figure 2: Left: The writer's model of a Half-spring frame, scaled to a Spring-hole diameter of 2 Roman *unciae* (4.9 cm), based on the following interpretation of Vitruvius' rhombus figure. The plating described by Heron has been added. Right: Len Morgan's photo of his oak frame under construction to Vitruvius' 2 *librae* size, with a Spring-hole diameter of 5 Roman *unciae* (12.3 cm). The semi-circular cutout for the arm in the Side-stanchion has not yet been made. The position of the tenons on the inner face of the stanchions is based on the evidence of Heron's rhombus diagram in figure 4.

Hole-carriers (*scutula*, i.e. *rhombus*)

4. cum ergo foraminis magnitudo fuerit instituta, describatur scutula, quae Graece περιτρητος appellatur, cuius longitudo foraminum II*F*[1] , latitudo III[2] et sextae partis[3]. dividatur medium lineae descriptae, et cum divisum erit contrahantur extremae partes eius formae, ut obliquam deformationem habeat longitudinis sexta parte, latitudinis ubi est versura quarta parte. in qua parte autem est curvatura <et>[4] in quibus procurrunt cacumina angulorum, eo[5] foramina convertantur, et contractura latitudinis redeat introrsus sexta parte. crassitudo eius foraminis I[6] constituatur.

4. *So when the size of the hole has been decided, let a rhombus be drawn, which is called* περιτρητος *in Greek* [**peritretos** = "pierced around" = **hole-carrier**], *whose length is* ***26/16** h.****,* *width* ***3* and one sixth h.***.

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[1] VEL mss ; VIII Granger ; IIEZ Schramm-Diels, Marsden. The V seems to be a misreading of the numeral II ; I suggest that the E is a failure to recognise the digamma *F*, and the L is dittography of the first letter of the following word.

[2] DUO mss. See commentary.

[3] et sextae partis mss ; et S Schramm-Diels, Marsden.

[4] <et>in quibus<partibus> Marsden . partibus can be inferred.

[5] et mss ; eo Schramm-Diels, Marsden.

[6] SI mss ; [S] I Schramm-Diels, Marsden (dittography error).

Let the outline which has been drawn be divided in the middle, and when it has been divided let the outer parts of that figure be drawn in so that it has the slanting shape, with ***one sixth*** *of its length equal to* ***one quarter*** *of its width at the angle. Moreover in the area where the curvature is and where the points from the angles extend, let the holes* [for the **washers**] *be drawn there, and let there be an inward reduction of the width by* ***one sixth****. Let its thickness* [the **hole-carrier's**] *be* ***1 h.****.*

<u>Commentary:</u>

The rhombus figure described in Vitruvius' turgid Latin, is based on a rectangle ABCD**.** Divide the rectangle at EF, and complete the rhombus outline GBCE (figure 3). This gives the slanting shape for the Hole-carriers. Diagonals from

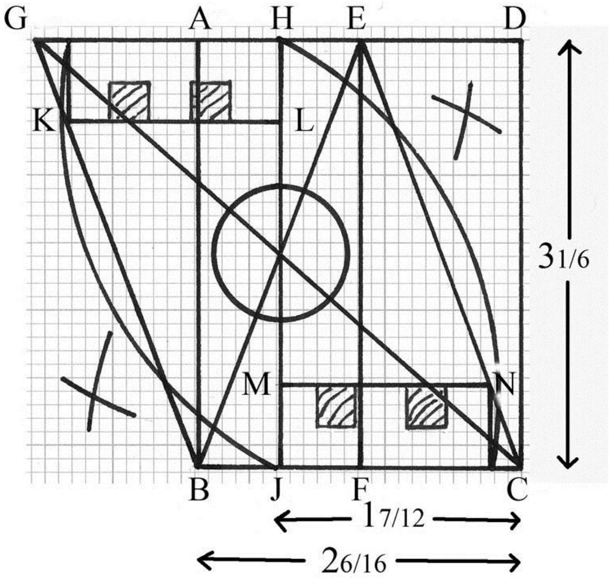

Fig. 3 : Vitruvius' rhombus. This gives a similar result to Heron's, but is achieved by a more complex procedure (see Fig. 4 and comments below).

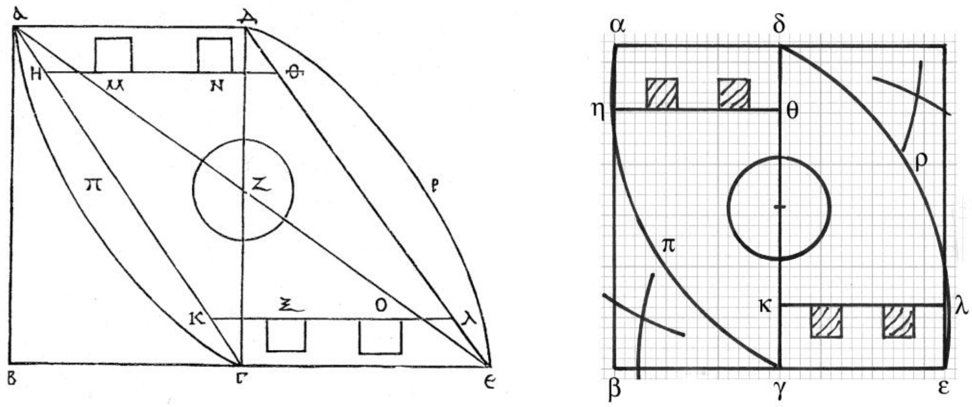

Fig. 4 : (left) ms version of Heron's rhombus diagram (after Wescher). Copyists have stretched the figure horizontally : Heron states that the long sides, AB and ΓΔ , of his rectangle are twice the length of the short sides AΔ and BΓ. Heron's method of drawing the rhombus, based on this simple rectangle, is much clearer. (right) The main details of Heron's diagram redrawn to correct the horizontal distortion. The ms diagram gives the side-stanchions improbable and impractical angled ends, presumably a copyists' error. So I have moved the ms lines HΘ and KΛ to the left.

the corners of the rhombus will give the centre of the spring-hole and the baseline HJ for drawing in the positions of the Side- and Centre-stanchions 11/18 thick and 17/12 (Ph.) wide. To add strength near the spring-hole and to trim off excess wood and weight elsewhere, the long sides are given curvature by drawing arcs "*whose radius is 3*" (H. *Bel*. 94-6); the centres of these arcs are marked in figures 3 and 4. From this rhombus the outline of the hole-carriers (figure 2) is created, a geometric solution to the need to increase the strength of the hole-carriers where they have been weakened by drilling the spring-hole. The same outline can be achieved by drawing Heron's solution and sizing it to a square with 3 1/6 sides (figure 4).

The key to solving the numeral for the width of the rhombus is the limit set by the need to allow room for the Spring-hole plus the thickness of the Side- and Centre-stanchions, plus the spacing between the stanchions and spring-hole required to accommodate the Arm and the bulk of the Rope-spring as it wraps round the Arm. For the bolt-shooting *scorpio* Vitruvius gives this spacing as ¼ h.; however his very special *ballista* Washers (see below) allow more than the standard amount of spring-cord to be inserted. This suggests a calculation of 1h.+11/18h.+11/18h + at the very least 5/18h.+5/18h. = 2 14/18h.. Therefore retaining the ms reading of 21/6 h. is impractical. This explains why I have suggested changing the ms reading **duo et sextae partis** to **III e.s.p.**, producing the same Hole-carrier profile as Heron's.

The top and bottom Hole-carriers on the left must be matched by a mirror-image right-hand pair. "*Let the thickness* [of the Hole-carrier] *be 1*". Philon's Hole-carriers are also this thick. It is important to cut the Hole-carriers so that the grain of the wood is running parallel to the long, curved sides. Their tops will be covered with a metal plate in addition to the plating round their sides (see below: PLATING).

Washers (*modioli*). Counter-plates (not mentioned by Vitruvius)

5. modioli foraminum II, latitudo IS9[7], crassitudo praeterquam quod in foramine inditur SΓ[8], ad extremum autem latitudo foraminis IΓ[9]. foramen[10] autem oblongius sit tanto quantam epizygis habet crassitudinem. cum deformatum fuerit, circum levigetur[11] extremam ut habeat curvaturam molliter circumactam.

5. *The **modioli (washers)** are **2 h.**, width **13/4 h.**, their thickness, except for the part which is inserted in the* [**Hole-carrier**] ***hole** is **14/16 h.**; but at the edge their width is **13/16* h.** Now let the* [**washer-**]***hole** be longer than it is wide by the thickness of the **epizygis (Washer-bar)** ; when it has been cut out let it be smoothed all round so that it has a gently curving outer edge.*

The Washers are **2** long, **1**¾ wide (**13/16** at the edges), **14/16** high excluding the part [i.e. flange, **1/5** (Ph.) thick] inserted in the Hole-carrier. The Washer-hole is to be longer than it is wide by the thickness of the Washer Bar. Vitruvius is describing an advanced type of Washer, otherwise unknown, with an oval Spring-hole which compensates for the space taken up by the Washer Bar and so allows vital extra spring-cord to be inserted. Catapult Washers are usually circular and cast in bronze.

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[7] I.S9 H , and so erased in S ; ISq ::: G ; I 5/12 Schramm- Diels, Marsden.

[8] SI H ; S.Γ S.

[9] I Γ. S ; I I ceteri . S Schramm-Diels, Marsden.

[10] foramen......circumactam: since this part of paragraph 4 can only refer to the modioli, I have transferred it to follow the sentence on the modioli.

[11] dividatur mss ; levigatur Krohn ; circumlaevigentur Schramm-Diels ; circumlevigentur Marsden ; delinatur Rose .

The thickness reading of **14/16** seems to be confirmed by the fact that Philon's Washer for a slightly smaller spring-frame is **¾** thick.

The sheer bulk of these Vitruvian Washers (figure 5) on a large stone-thrower requires them to be made of plated wood, because huge bronze castings would be impractical.

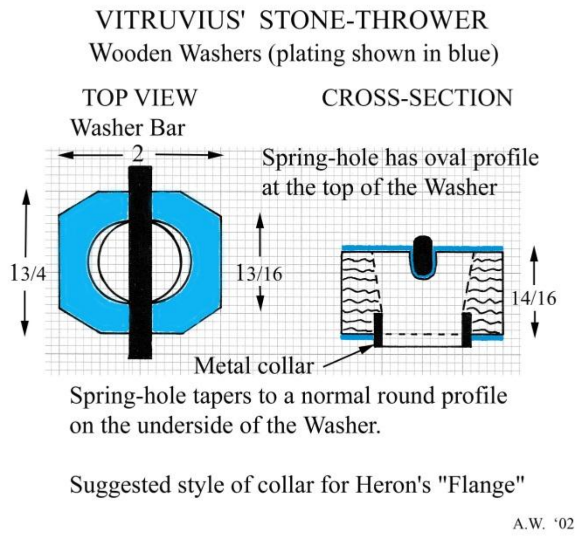

Fig. 5 : Vitruvius' Washer. Top and bottom plating shown in blue. The sides should also be plated.

Heron *Bel*. 96-7 remarks that for larger machines, if the Washers are made of wood the grain must run vertically, (as in a modern butcher's block), and that reinforcing plates must be pinned to the top and undersides. He adds that the underside of all Washers must have either a flange or two round tenons to lock into a round groove in the Hole-carrier. *"A flange may be formed all round which runs in a circular groove cut in the hole-carrier, to stop the washer moving out of position."* (H.) All the many bronze washers that have been found have such a flange, for example the fine Hatra Washer (figure 6) which is complete with its 5 mm thick bronze Counter-plate which "*prevents the Hole-carrier being worn away in the area of the groove*." (H.)

Fig. 6 : The Hatra washer: (left) with square counter-plate. (right) showing bottom flange. (Baatz, 1978b, Abb. 10 & 11)

I have used the large wooden washers on my scale model (figure 18). Len Morgan has used standard bronze washers with round internal spring-holes on the 2 *librae ballista*, the smallest *ballista* on Vitruvius' list. Because it is extremely difficult to make round bronze washers with oval internal spring-holes, it is likely that we have not been able to cram as much extra spring-cord as Vitruvius' plated wood examples would have allowed.

Washer Bars (not described by Vitruvius)

A Washer Bar, around which the spring-cord is tensioned, and which is used to apply twist to the springs, "*is to be of pure iron, well-finished in the hearth, because it must withstand the whole force of the machine*." (H.)

Philon's bars are **1/5** thick, **2/5** wide [i.e. high], but his machine has slightly less spring-cord. In view of the enormous force operating on the Bar, we should probably try something like ¼ for the thickness and ½ for the height. Too much width will reduce the space for the spring-cord and defeat the object of the oval hole. A length of 2½ will give plenty of overhang for a tightening spanner.

Note the "bow tie" profile of the bars on the Caminreal Frame (figure 7); this stops the bars slipping when applying the spring-cord, and strengthens the ends where the tightening spanner is applied.

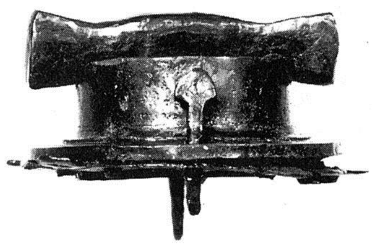

Fig. 7 : Caminreal washer and bar with "bow tie" profile (JRMES Volume 8 1997, 175 Fig. 13).

The spanner is mentioned by Heron *Bel*. 101-2 : *"Once the arms have been pushed through the middle of the springs, you must twist the washers with an iron bar which has a ring into which the projecting part of the washer bar is inserted. This is so that the arms may have the recoil mentioned."* This design of bar and ring spanner is illustrated by Anonymus Byzantinus (Wescher, 1867, 254).

Side-stanchions (*parastatae*)

parastatarum longitudo foraminum VSΓ[12], curvatura foraminis pars dimidia, crassitudo foraminis CC[13] et partis IX[14]. adicitur autem ad mediam latitudinem quantum est prope foramen factum in descriptione.

The length of the ***parastatae (side-stanchions)*** *is* ***511/16* h.*** *; the curve of the* ***hole*** [cut out for the **arm**] *is* ***half h.*** *; their thickness is* ***11/18* h.****. But an amount is added to their width in the centre approximately as large as the* ***hole*** [cut out for the **arm**] *in the drawing.*

Construct left and right Side-stanchions **511/16*** high, **11/18** thick and **17/12** (Ph). wide (Fig. 2). In the centre of the rear edges a semicircular cutout is made "*to allow the arms even more room to recoil*" (H.). "The cutout is ½" [radius rather than

[12] V.S. H ; V.S.Γ. S (Selestad ms) ; VΓ Schramm-Diels, Marsden.

[13] CC mss ; S Schramm-Diels, Marsden . Both symbols = 1/2.

[14] LX mss ; IX Schramm-Diels, Marsden.

diameter, to judge by the thickness of the arms]. On their leading edges "*an amount is added to their width in the centre approximately as large as the hole* [cut out for the arm]". A similar curve is added to the frames of bolt-shooters (see Caminreal plating and Xanten profile (figure 8); also the Vedennius relief (figure 9). Heron *Bel*. 94 describes double tenons at the ends of the stanchions, which penetrate about two thirds of the Hole-carriers' thickness. The diagram in the mss of Heron (figure 4) shows square section tenons, but Heron's instruction to "*put circular plates round the double tenons, fixed with nails*" seems to imply round ones. I have come to the conclusion that the Greek word *kuklikos* , which normally means "circular", is intended to mean "encircling", "encasing", "sheathing" here. Somehow the tenons are to be encased in metal reinforcing plates.

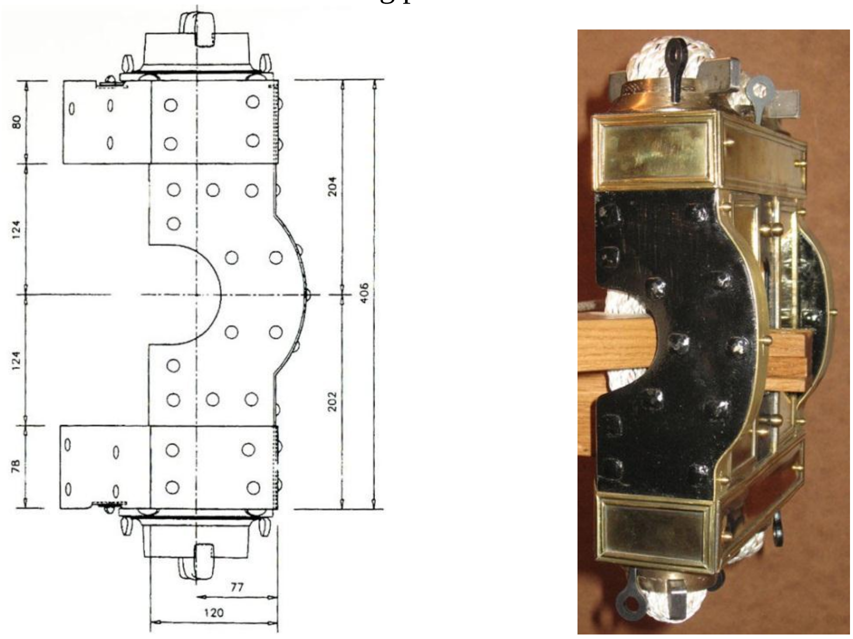

Fig. 8 : (left) Side-stanchion plating of Caminreal bolt-shooter, with front curve. JRMES Volume 9 1997, 179 Fig. 19. (right) Side-stanchion curve on a replica of the Xanten Two-span bolt-shooter.

Fig. 9 : Relief of a bolt-shooting *catapulta* (probably a Two-span) on the tombstone of *arcitectus* Vedennius Moderatus, showing the front curve of the side-stanchion and details of the plating and bolt heads (Vatican Museum).

<**Tenons**> (<***cardines***>)

<cardines> [15] latitudine et crassitudine foraminis V, altitudo parte IIII.

*<The tenons> are **1/5** wide and thick, **¼*** high.*

The name of this part/parts is missing from the mss. Components of such small dimensions sound like square pegs of some kind. I believe them to be the same as Heron's eight tenons which he clearly describes (*Bel*. 99 in Appendix 1) as protruding from the Hole-carriers and penetrating the Crossbeams.

The extra detail from the Vatican ms (shown in Wescher's drawing, figure 10) restores the label τορμος (tormos) on Heron's diagram, and confirms that there were two tenons on the front and rear faces of each Hole-carrier. Heron's text gives reference letters for all the parts. Unfortunately our copies of his diagram do not have them.

Vitruvius describes the part(s) as **¼*** high, which could mean that they were tenons which projected ¼ from the surface of the Hole-carriers, and therefore would have penetrated halfway into the Crossbeams. They would have ensured that the Crossbeams are locked in the correct position on the surfaces of the Hole-carriers. See the plan of the front framework in figure 14. My model (figure 18) shows the Crossbeams' positions relative to the Hole-carriers.

Centre- or Counter-stanchions and Heel-pads.

These are straight-sided versions of the Side-stanchions, missing in Vitruvius' text as transmitted. The Greek term for them in Heron is *antistates*; he describes them as lacking the convex and concave shape of the Side-stanchions, but with the same length and a similar vertical double tenon each end. They have "*a pad to meet the heel of the arm as it recoils against the stanchion*." (H. *Bel.* 93) (visible on my model, figure 18). This confirms the fact that the inner ends of the catapult's arms were allowed to strike the Centre-stanchions, as part of the braking system absorbing the force of the arms' forward travel. The bowstring acts as the main brake, as Heron's remark in *Bel.* 102 makes clear: "*It is necessary to tighten the bowstring enough to hold the arms a short way clear of the side-stanchions, so that they are not damaged and do not cause damage.*" Some of the forward energy will be absorbed by the missile itself, of course. The validity of Heron's advice was proved by the damage caused to the BBC's One-talent stone-thrower when the bowstring stretched and the arms struck the massive (unplated) oak side-stanchions causing them to crack. To be fair to the BBC team, the correct rope for the bowstring failed to arrive in time, and the synthetic rope used was not prestretched.

PLATING

The two Half-springs are mirror images of one another. They can be used as the templates for cutting the iron reinforcing plates.

It was standard practice in Greek and Roman engineering to reinforce wood with bronze or iron plates or collars. This was intended to add strength at critical

[15] Gap in mss. <regulae> Schramm-Diels, Marsden. From their small dimensions I suggest <cardines>. See commentary above.

points and to combat wear. In catapults a side benefit of plating was to combat fire. Heron makes some general points about the stone-throwing catapult in *Bel.* 102 (Marsden's translation revised): *"It is essential to provide iron plates at critical points, I mean points that are under strain, and fasten them on with nails. Use strong timber and strengthen the places mentioned in every possible way. However construct the parts not under stress of light and small pieces of wood, as you make your assessment of the parts that hold the catapult together and of the bulk and weight of the machines. For very few catapults are built to meet urgent crises. So they must be easily dismantled for transportation, light and inexpensive."*

He gives specific instructions about the stanchions of the spring-frame (*Bel.* 92-3): Side- and Centre-stanchions are to be "*covered on both sides with plates fastened with nails*". In *Bel.* 94-5 he states that *"The hole-carriers must be made of strong timber and must have plates put all round their vertical sides and fastened with nails…"*

No plating from stone-throwers has been identified to date, but there are the Ampurias, Caminreal and Xanten metal plates from the spring-frames of bolt-shooters. Their stanchions and hole-carriers have been plated as Heron recommends. The plates are pinned on with nails, or rivets. The exemplary Caminreal report gives the exact sizes and details of which are rivets etc. (*JRMES* 8, 1997, figure 18) See also the side rivets reproduced on the relief of Vedennius (figure 9).

2. THE INTERLOCKING CROSSBEAMS AND CROSSBARS

The pair of Half-springs is locked in position by an outer framework composed of the following beams and bars, identifiable in Heron's main diagram (figure 10), although there the Crossbeams are drawn as straight. Schramm and Diels' conflated the three engineers' texts and published a single diagram for the "Palintonon according to Heron, Philon and Vitruvius", the first version of which showed the Crossbeams as straight; their second, final version (figure 17) showed the Rear Crossbeam as curved. Vitruvius clearly describes both as curved, as Marsden emphasised.

Vitruvius begins by describing the two lower Crossbeams :

Rear Crossbeam (*regula in mensa* "the beam on the Table")

6. regulae quae est in mensa longitudo foraminum VIII, latitudo et crassitudo dimidium foraminis. cardines ΓZ[16], crassitudo foraminis 9[17]. curvatura regulae IϚ [K].[18]

*The length of the beam which is on the Table is **8**, the thickness and width is **half**. Tenons* **5/8****[long], ***¼**** *thick. Curvature of beam* ***19/16****.

Philon gives the Crossbeams' width as **5/9**, their thickness **4/9**. For the tenons see below under CROSSBARS.

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[16] IIZ ::: <u>mss</u> ; II <u>Schramm-Diels, Marsden</u>. I suggest ΓZ (see commentary).

[17] I99 <u>mss</u> ; 9 <u>Schramm-Diels, Marsden.</u> (Probably FORAMIN<u>IS9</u> was miscopied and repeated as I99.)

[18] I Ϛ.K <u>mss</u> ; S9 <u>Schramm-Diels, Marsden.</u> (The many K's in this section of the mss may well be referring to one of the lost diagrams).

The name "beam on the Table" implies that this Inner Crossbeam was in contact with the Table (and that the Outer Crossbeam was not). For the realisation of this see figures 14 and 18.

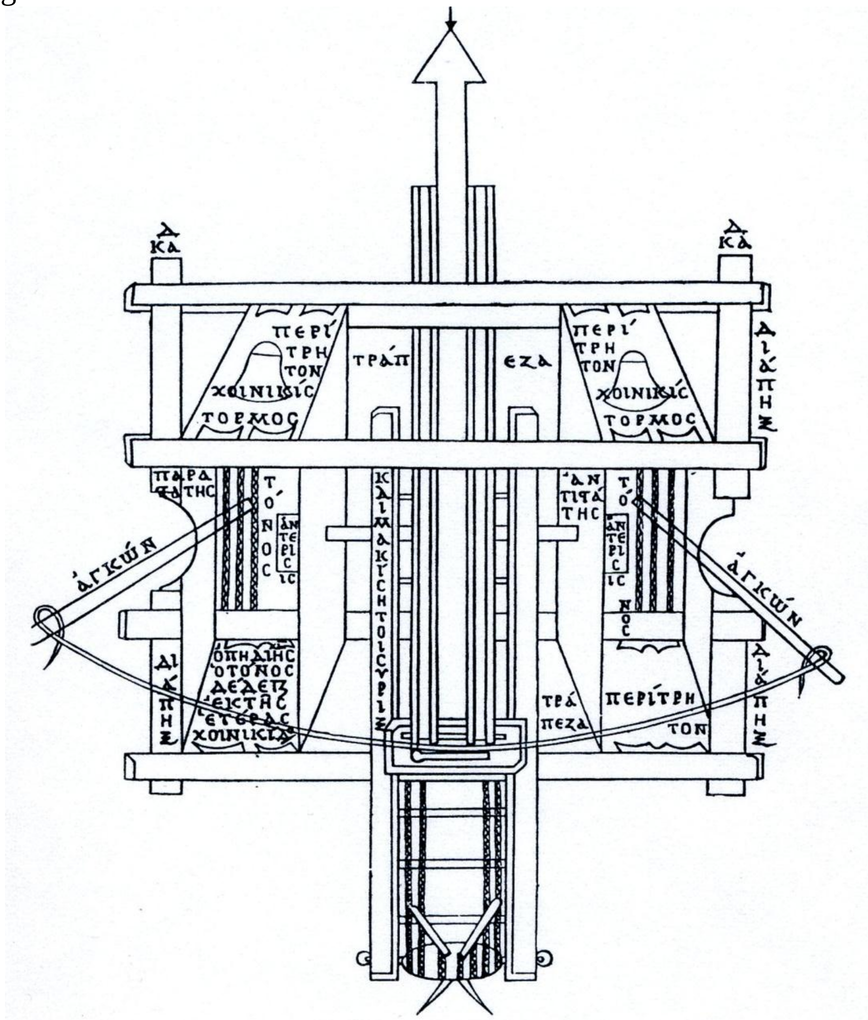

Fig. 10 : Heron's diagram of the *ballista* redrawn by Wescher, combining the figures in mss P and V.

The curvature of **19/16** is probably the deviation from straight caused by the central "bend" which helps to maintain the important contact between the Crossbeam and the curved profile of the Hole-Carriers.

Fig. 11 : Len's Crossbeams with top plating. The straightened central part of the Outer Crossbeam helps to maintain the spacing between the two Hole-carriers. (photo: Len Morgan)

Outer Crossbeam (*regula exterior*)

exterioris regulae latitudo et crassitudo tantundem, longitudo quam dederit ipsa versura deformationis et parastaticae latitudo ad suam curvaturam [K].

The Outer Crossbeam's width and thickness are the same" [as the inner Crossbeam] *; its length is what the actual angle of inclination* [of the Hole-carrier] *and the width of the Side-stanchion add to its curvature.*

This seems to mean that the beam is shaped to follow the contours of the front edges of the Hole-carriers. To keep the wood grain following the complex curves, the Crossbeam may have been made from layers of laminated timber cramped into shape against the assembled catapult parts or a former - a technique used to produce curved legionary shields, as shown by the Dura Europos finds. As I discovered when using the laminated approach on my model (figure 18), the initial length of the laminated layers has to be far more than one would expect, because cramping the them to follow the contours of the Hole-carriers will shorten their actual span.

It should probably be strengthened with plates at least along its outer face, and perhaps on its top and inner face as well. (See below - CROSSBARS - for plating the halving joints at the ends of Crossbeams and Crossbars.) Figure 11 shows Len Morgan's modified, fully plated design with a straightened central portion to maintain the spacing between the two hole-carriers.

Fig. 12 : Details on the Mk I machine of one of the plated Crossbars joined to the ends of the Crossbeams by halving joints and pins. Also visible are the two metal straps which are Len's addition to secure the Crossbeams to the Hole-carriers, and the ends of the two bolts used as the Locking Bars.

Upper Crossbeams (*regulae superiores*):

superiores autem regulae aequales erunt inferioribus [K].

The Upper Crossbeams will be equal to the lower ones.

Crossbars

The three engineers do not mention these essential components, but all four bars are shown clearly in Heron's diagram (figure 10), where they are labelled διαπηξ (diapex = Crossbar). (They are not mentioned in Heron's text as transmitted). They sit flush with the outside edges of the Hole-carriers and link the ends of the Crossbeams.

*Tenons 5/8***[long], *¼* thick*. The thickness of ¼ for the tenons of the ½ thick Crossbeams suggests that halving joints were used at these junctions, and not the much square tenon system shown by Schramm and Marsden (figures 16 and 17).

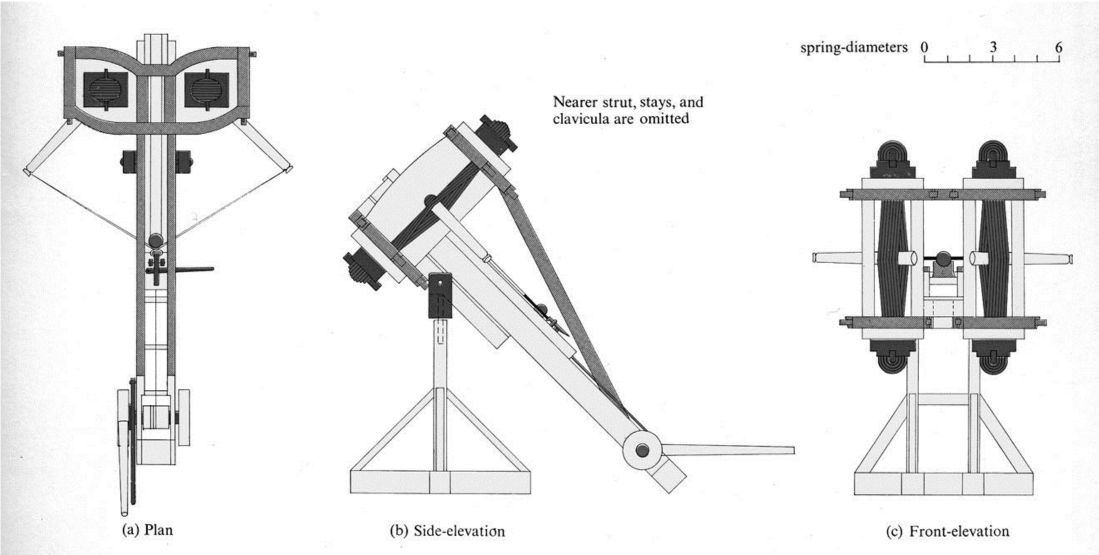

Fig. 13 : Marsden's *ballista* plan (Marsden 1971, Diagram 11 opposite 204).

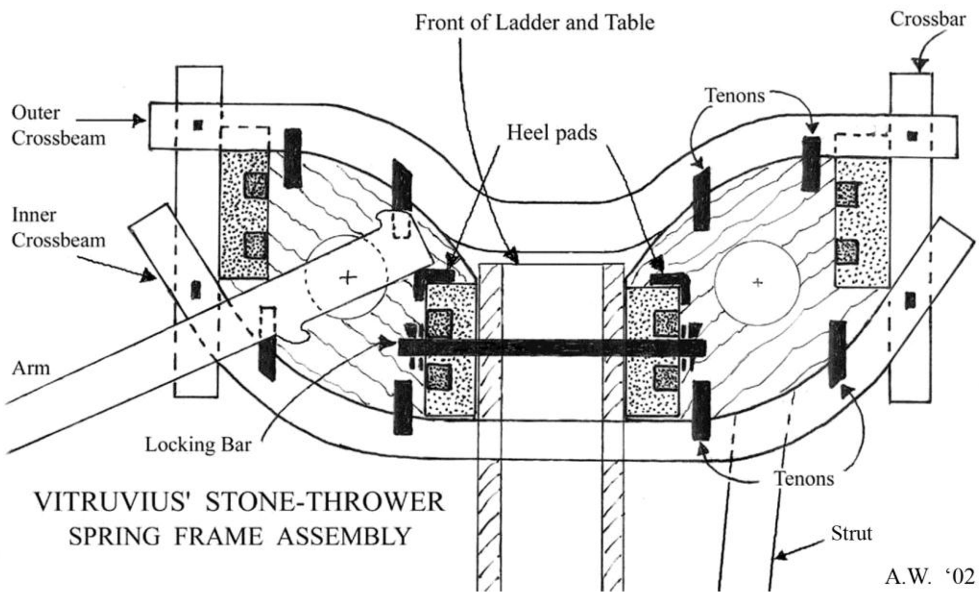

Fig. 14 : My original drawing of the Spring-frame and Locking Bar from above, along with the positions of the Ladder, the right-hand Stay/Strut and left-hand Arm. Heron's eight tenons are discussed in the adjacent section CROSSBARS. In following the evidence of Heron's drawing (figure 10) I have extended the Crossbars and Crossbeams far too much beyond their halving joints: see comments above. For Len's treatment of these overlaps see figure 11.

This appears to be confirmed by Heron's diagram, which shows all eight Crossbeams and Crossbars projecting a small amount beyond each other at the ends. The 5/8 tenon length would allow the halving joints to project very slightly, 1/8, beyond the joints themselves. This would reduce the chance of end-grain splitting. Some form of metal capping may well have been applied to their ends, an idea which gains support from the remarkable bronze sheathings from the ends of the wooden frame of the 3rd century AD Hatra stone-thrower (Baatz 1978a, 4, Fig. 3).

There is no evidence at all in the texts or Heron's diagrams for the extra Crossbars which Marsden inserts along the inside edges of the Hole-carriers ; on his small model (figure 15) they are joined to the Crossbeams by halving joints ; such joints would seriously weaken the Crossbeams at a critical point. In his diagram (1971 55, Fig. 18) these extra beams appear as ΧΨΦΩ ; but these are the very letters which Heron's text (*Bel*. 99) gives for the rungs or cross-pieces of the Table. Of course Marsden was right to be worried about the centre sections of the Crossbeams being under stress from the torsional forces applied to the Half-springs when the arms are wound back and recoil. Len has plated the Crossbeams on all sides, creating strength at the ends where they are pinned through the Crossbars (figure 11 again).

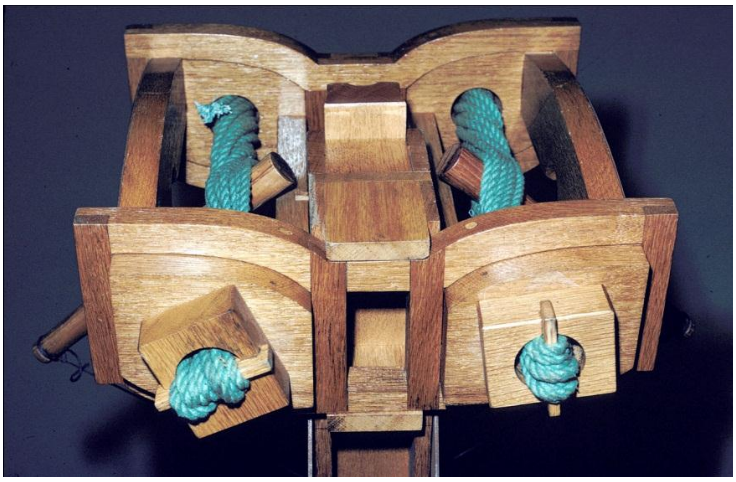

Fig. 15 : Small model *ballista* made for Eric Marsden by Norman and Raymond Cooper. Halving joints are used to link the ends of the Crossbeams and Crossbars; this may have been Eric's final verdict on these joints. Note the extra Crossbars inserted along the inside edges of the Hole-carriers : see the commentary above.

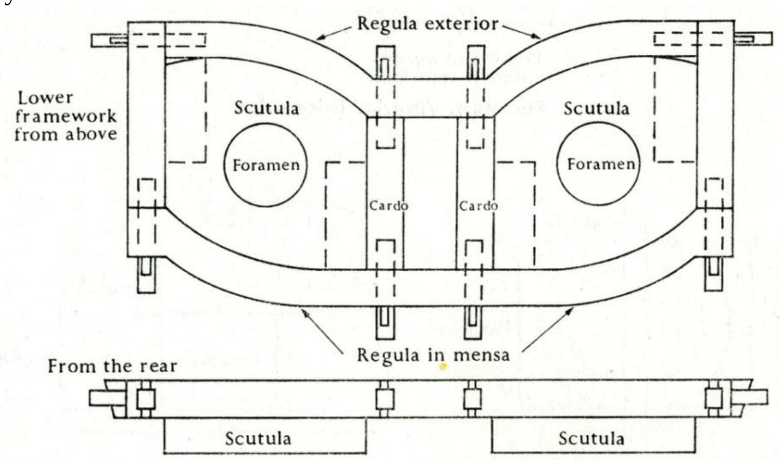

Fig. 16 : Marsden's plan of the framework (Marsden 1971 202 Fig. 10).

ASSEMBLY 2 : THE SPRING-FRAME

Line up mortise holes in the Crossbeams with the tenons protruding from the Hole-carriers, and tap them into place. Do not glue these joints because Heron says that most parts of the machine can be dismantled for easy transportation. He also says that you must provide iron plates at all points which must withstand hard usage. As already suggested, the outer vertical faces of the Crossbeams and Crossbars (and possibly the horizontal faces, too) should be plated. The Crossbars must have been held in position at the ends of the Crossbeams by some sort of pins driven through the halving joints to tighten the fit of the Crossbeams to the Hole-carriers (figure 18). See figure 11 for Len’s version, which showed no signs of problems in early tests.

The completed assembly of Crossbars, Crossbeams and Half-springs may be called the Spring-frame. Two features help to fasten it securely to the stock of the machine: a Locking Bar and two Struts.

COMPONENTS JOINING THE SPRING -FRAME TO THE STOCK

Locking Bar

Marsden invents a pair of giant wedges inserted into the back of the Inner-stanchions and pressing down on the top edges of the Ladder. In practice, those on his model keep working loose.

However, Heron’s diagram (figure 10) clearly shows a beam or bar passing through the Centre-stanchions and apparently passing through the Ladder. In conjunction with the Struts, this would provide the means of locking the Spring-frame to the stock at a point close to the line of bowstring and arms, and so ideal for taking the enormous strain when the Slider is wound back. It must surely have been substantial and of iron, and the holes for it as it passed through the Centre-stanchions and the Ladder’s Side-poles would probably have been reinforced with metal collars; it would be essential to have metal pads at its ends, against which the bar could be tightened by, for example, wedge-shaped pins.

Enlarging Wescher’s version of Heron’s diagram makes it possible to read the label αντερισις (anterisis) on two rectangular blocks drawn on the inner faces of the Inner Stanchions. The Greek word could be an otherwise unknown noun from the verb αντεριζειν (anterizein) meaning “to strive against / to resist”; or it may be a misspelling of the known noun αντειρις (anteiris). In either case the noun will mean “buffer” or the like, and would then appear to be labelling blocks at the ends of the Locking Bar which would function as the metal pads suggested above.

Len has used two bars, one passing through the Table, the other through the Ladder, visible in figure 12 as modern threaded bolts used for ease of assembly/ dismantling.

Struts (*anterides*)

9. anteridon longitudo foraminum XVIIS[19], latitudo in imo foraminis Γ[20], in summo crassitudo F[21] [K].

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[19] foraminum eius latitudo <u>mss</u> ; I suggest that EIVS is a corruption of XVIIS. foraminum III9, latitudo <u>Schramm-Diels, Marsden.</u>

[20] . Γ <u>mss</u> ; S <u>Schramm-Diels, Marsden</u>.

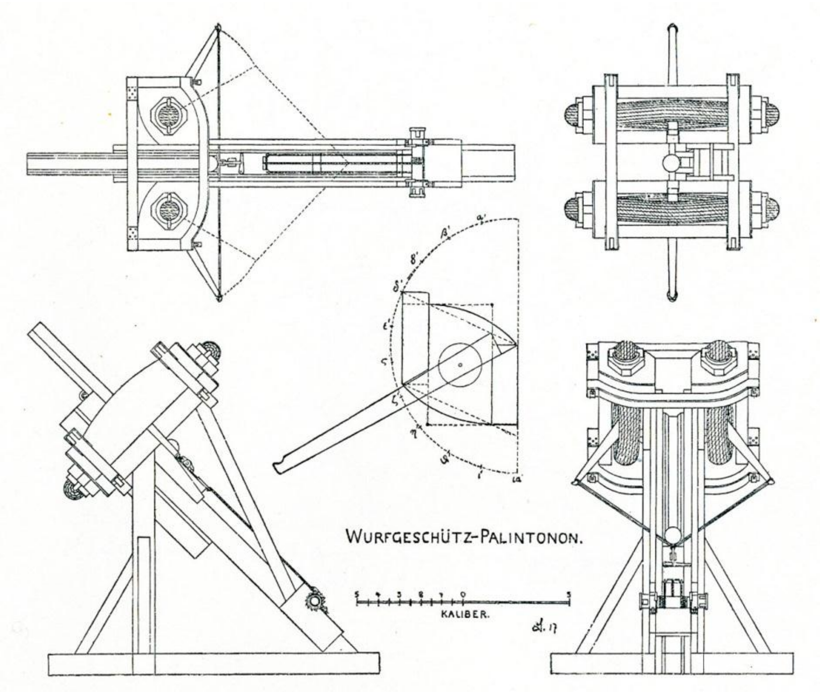

Fig. 17 : Schramm's plan, dated 1917, of his Palintonon, combining the evidence of the three engineers. His Struts are fastened to the sides of the Ladder's side-poles (Schramm, 1918, 56, Abb.22).

*The struts are **17*½** long, **3/16** wide at the bottom, **6/16*** thick at the top.*

"*The Half-springs have struts* (anterides) *whose bottom ends are fastened to the Ladder, the top ends to the upper Hole-carriers, so that the Half-springs are not strained while the pull-back is taking place.* (H. *Bel*. 101) On all reconstructions known to me, except Schramm's in figure 17, the top ends are fastened incorrectly to the inner Crossbeams. My solution of 17½ , XVIIS, for the corrupt figure for their length EIVS, is palaeographically straightforward and, as Len confirms, works well in practice.

Schramm's Struts are shorter and fastened to the sides instead of the tops of the Ladder's Side-poles. Philon does not mention the Struts. They are mounted running parallel to one another on all existing reconstructions, but on my model and diagram (figures 14 and 18) I tried splaying them, to reduce possible twist between the frame and stock. Experience with parallel mounted Struts on our 2 *librae* machine suggests that this is unnecessary.

Vitruvius' dimensions – width at one end and thickness (usually = height) at the other end - strike me as odd. He does not give a straightforward width and height for the stays. I believe that he may be giving a reduction in width/height at their ends which is required to attach them to the Side-poles of the Ladder and to the Hole-carriers. So their main width and height must be estimated – 3/8 wide and ½ high, or even thicker – say ½ by 5/8?

THE STOCK i.e. TABLE, LADDER, SLIDER AND WINDLASS

mensae transversarii foraminis CCC[22][K]

[21] F . K mss ; Γ Schramm-Diels, Marsden.

[22] CCCK mss ; 9 Schramm-Diels, Marsden. (CCC = 3/4. C = Γ, I believe.)

Fig. 18 : My large model (stock one metre long, scaled to a spring-hole diameter of 4.9 cm, 2 Roman inches) used as the basis for Len’s full-size machine. It has the wooden Washers described by Vitruvius and Heron (p. 7-8 and figure 5). I have also added Philon’s thick counter-plates under the Washers (Appendix 2 for corrected reading of his text): he gives their thickness as one quarter of the diameter of the spring-hole, too thick for them to be cast in metal, so I have presumed them to be plated blocks of wood. They are not mentioned by Vitruvius, and are omitted on our Mk I version. The bowstring on the model is far too narrow, and there is room for a lot more spring-cord.

7. climacidos scapi longitudo foraminum XVIIII[23], crassitudo I[24][K]. intervalli medii latitudo foraminis et partis quartae, crassitudo pars VIII[25][K]. climacidos superior pars, quae est proxima bracchiis atque coniuncta est mensae, tota longitudine dividatur in partes III[26]. ex his dentur duae partes ei membro quod Graeci χελωνιον vocant, latitudo IΓ[27], crassitudo *9*, longitudo foraminum XII et semis [K][28]. extantia

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23 XIII mss ; XVIIII Schramm-Diels, Marsden. (Philon gives 19 as the length.)

24 IK mss ; 9 Schramm-Diels, Marsden.

25 crassitudo pars .VIII.K H ; altitudo foraminis I et partis octavae Schramm-Diels, Marsden. (A puzzling treatment of the mss reading, attempting to make the text refer to the height of the scapi as 1 1/8, where the mss are giving the thickness of the intervallum medium or "central gap" as 1/8.)

26 partis .v. H ; partis .u. G ; partes V Schramm-Diels, Marsden : if the length of the χελωνιον (Slider) is 12½ it is two thirds of the Ladder's length of 19, certainly not two fifths. So I suggest partes III.

27 latitudo Γ crassitudo 9 mss ; lat. IΓ, crass. 9 Schramm-Diels, Marsden.

28 III & semis .K. mss ; XI et semis Schramm-Diels, Marsden . XII et semis is closer to two-thirds of 19.

cheloni foraminis S, pterygomatos foraminis Z et sicilicus[29]. quod autem est ad axona, quod appellatur frons transversarius foraminum trium.

8. interiorum regularum latitudo foraminis *F*[30], crassitudo ζ[31] [K]. cheloni replum, quod est operimentum, securicula includitur [K] in scapos climacidos : latitudo <I>*G*[32], crassitudo foraminis XII[33] [K]. crassitudo quadrati quod est ad climacida foraminis *F*, C[34] in extremis [K]. rotundi autem axis diametros aequaliter erit cheles, ad claviculas autem [35]minus parte sexta decuma [K].

*The **transversarii** (**cross-struts**) of the **table** are ¾*** h.***

*7. The length of the **scapus** (**side-pole**) of the **ladder** is **19* h.** (= Ph.), its thickness **1* h.**. The width of the **intervallum medium** (**central gap**) is **one and a quarter h.,** its thickness **1/8 h.**. Of the **climacis** (**ladder**), which is very close to the **bracchia** (**arms**) and is joined to the **table**, the total length of the upper* [i.e.top] *part is divided into **3*** sections ; of these **two** sections are given to that component which the Greeks call χελωνιον* [**chelonion =** "tortoise-shell" or "trough", apparently used for the **slider** and/or the groove for the missile] *, **13/16* h.** wide, **4/16 h.** thick and **12* and a half** long. The **extantia** (**upstanding part**) **of the chelonion** is ½ **h.**. The **pterygoma** (**wing**) is **7/16 h. and a quarter.***

*As for the **axon** (**axle**) [of the windlass ?], what is termed the width across is **three h.**.*

*8. The width of the **interiores regulae** (**inner beams**) [i.e. rungs of the **ladder**] is **6/16* h.**, their thickness **7/16* h.**. The **replum** (**cover**), that is the **operimentum** (lid) for [i.e. the base for] the **chelonion** is fastened by dovetail into the **side-poles** of the **ladder**, and is **<1>3/8# h.** wide, **1/12 h.** thick.*

*The thickness of the **quadratum** (**squared block**) which is added to the **ladder** is **6/16 h.**, **¼ h.** at the ends.*

*The diameter of the **rotundus axis** (**round axle**) [of the windlass] will put it on a level with the **chele** (**trigger / trigger block**), but will be **one sixteenth** less at the **claviculae** (**pawls**).*

Ladder (*climacis*)

Vitruvius records the following parts for this well-named component (Figs 15 and 21). Ladders are very common components in Greek and Roman engineering, combining strength with lightness.

Side-poles (*scapi*) : **¼** (Ph.)wide **x 1** thick [=high] **x 19*** (= Ph.)long.

Inner Beams (*interiores regulae*) : these are the rungs, **1¼#** long x **6/16*** wide x **7/16** thick. Philon says that they are spaced **4** apart.

"Wings" (*pterygomata*) : these are wedge-sectioned boards forming the sides of the female dovetail groove : **a quarter** [wide] **x 7/16** [high]. They are cut from the same

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[29] plentigomatos (*sic*, pterygomatos Turnebius) f. Z & sicilicus mss ; <ΠΤΕΡΥΓΩΜΑΤΟΣ> foraminis 9 Schramm-Diels ; pterygomatos f. 9 Marsden.

[30] .Γ. mss ; *F* Schramm-Diels, Marsden.

[31] .K. mss ; Γ Schramm-Diels, Marsden.

[32] *G* mss ; Γ Schramm-Diels, Marsden.

[33] XII mss ; duodecima Schramm-Diels, Marsden.

[34] foraminis F.C. in extremis mss ; foraminis 9 in extremis Schramm-Diels, Marsden.

[35] autem <S> minus Schramm-Diels, Marsden.

piece of wood which supplies the male dovetail of the Slider. Make the cuts at an angle of about 60 degrees.

Slider Cover or Lid (***cheloni replum, quod est operimentum***) : **13/8*** wide **x 1/12** thick, "*fastened by dovetail into the Ladder Side-poles*". I have interpreted this thin board as the base on which the dovetail of the Slider rests.

Central Gap (***intervallum medium***) : **one and a quarter** [wide] **x 1/8** thick. This gap between the bottom of the rungs and the Plank of the Table provides the space for the windlass rope which pulls the Slider forwards.

Figure 21 of the cross-section of these components offers a different interpretation from that of previous editors.

Squared Block : "*the thickness of the Squared Block which is added to the Ladder is* ***6/16***, *¼ at the ends*". There is no certainty as to what this looks like or where it fits. It may be the equivalent of the very similar block (*buccula*) on the back of the windlass box of Vitruvius' bolt-shooter. It would therefore seem likely that it was fastened to the rear end of the Ladder, using dovetails, as on the above-mentioned windlass box. Such a cross-piece would provide essential bracing for the Ladder.

Table (***mensa***)

This component also resembles a Ladder, but the plank on the top has earned it its nickname (figure 19). It is basically a spacer that lifts the Ladder and Slider to the height required to access the bowstring (figures 1 and 18), and provides a greater area of timber in contact with the Inner Stanchions. The recorded parts are :

Side-poles : (not mentioned in Vitruvius) Philon's figures are: **9** long. ¼ wide, **1** high.

Cross-struts (***transversarii***) : i.e. **rungs** **1¼#** [wide] **x** ¾ [high and thick].

Plank on the Table (σανις εν τραπεζη sanis en trapeze Ph.) (not mentioned in Vitruvius) : **1¾#** [wide] **x 1/8** (Ph.) [thick]. "*The plank fills the whole space between the Side-poles…..The Ladder is placed on the plank which lies on the Cross-struts*." (H.)

No mention is made of the method used to join the Ladder to the Table.

Fig. 19 : Len's Table, with the plank ready for fastening on top of the sides and cross-struts (photo : Len Morgan).

Slider (*chelonion* " trough")

13/16** wide, **6/16**** thick, **12* and a half** long. There are some problems with the measurements in the mss. I think that Vitruvius is saying that the top part of the Ladder is divided into three sections, two of which "*are given to that component which the Greeks call χελωνιον* [chelonion]" : i.e. the Slider (**12½**) is two thirds the length of the Ladder (**19**). Philon gives no figure for length, but just says it is *"in proportion"*. The projecting top of the Slider (***extantia cheloni***) is ½ high (cross-section Fig. 21). From calculations based on actual missiles and Vitruvius' list of weights and diameters, the missile itself was about **5/8** to **¾** in diameter.

THE SLIDER AND THE BOWSTRING

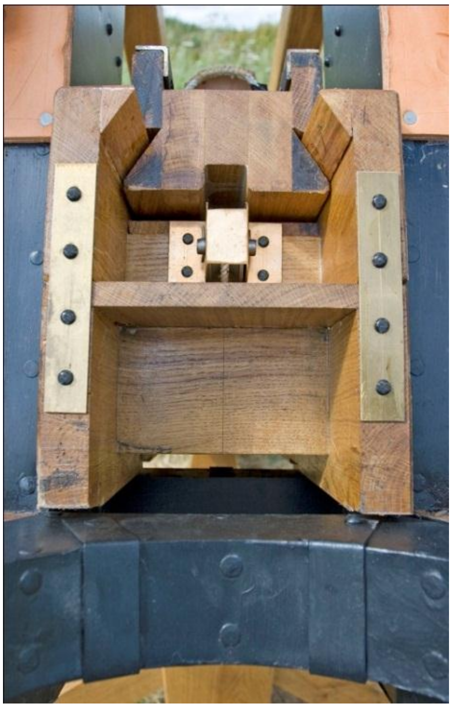
No information is given by the three engineers as to whether the missile groove was a shallow curved trough on the top of the Slider, as on bolt-shooting catapults, (which I found to be unreliable in tests), or whether the version on my model, with the stone missile running inside a square section trough, would reduce the chance of the stone ball jumping off the Slider, and also reduce friction and wear. It is significant that both Schramm and Payne-Gallwey, who conducted extensive experiments, chose the latter method. In tests with Len's full size machine we found this profile to work well, provided that the side-rails are kept low in order to allow the bowstring to contact the missile at the correct height. Heron's advice is crucial (*Bel.* 110-111): he says that unlike the round bowstring of the bolt-shooter, the palintone stone-thrower's *"...is flat, like a belt, and has loops at the ends where the arms fit. In the centre by the claw is a sort of ring plaited from the actual sinews of the belt*." Initial attempts to make the bowstring out of two ropes, only filled in like a band in the centre, allowed the bowstring to wobble and miss the centre of the missile. Len's impressive final version is fully belt-like and functions very reliably.

Fig. 20 : Len's final version of the bowstring belt, following Heron's description (photo : Len Morgan).

See now the following discussion in my article on the catapult balls from Qasr Ibrim, Egypt (Wilkins, Rose & Barnard 2006, 77), where ink inscriptions on different weights of stone assign them to an individual centurion. The hundreds of Qasr Ibrim balls were all weighed and carefully recorded in a remarkable *tour de force* by Dr Hans Barnard, and with vital contributions and backing by Dr Pam Rose, the current Director of Excavations.

The most difficult practical problem to solve is ensuring secure contact between the bowstring and the stone ball throughout the launch. That this was a major problem for Roman operators is made clear by the Alexandrian engineer Heron's advice on bowstrings (*Belopoiika* 111-2 in Marsden 1971, 38-9). He says that whereas the bolt-shooter's bowstring is round and close to the surface of the slider, the stone-thrower's is flat like a belt and further away from the slider, "*so that it will strike the stone half way up…. If it is positioned a little too high or low it will either slip under or jump over the stone*". We experienced the latter effect with the giant BBC *ballista* (Wilkins 2003, 58-9), when the 26 kg stone plopped harmlessly out of the machine. The slipping of the bowstring under the missile is a potentially lethal problem which can launch the missile upwards. Such an event almost changed the course of 20th century history when Major Schramm demonstrated his version to Kaiser Wilhelm II: the Kaiser had to be pushed out of the way of the descending missile (Wilkins 2003, fig. 8). Dr Barnard's invaluable information about the variety of shapes – "rough, well rounded, flattened, irregular, hemispherical, cubic and ovoid" – confirms that a semicircular launch channel, suggested for round profile missiles, would be unable to keep these irregular missiles at the required constant height to meet the bowstring in their centre.

The solution is a rectangular section channel, where the missiles sit on the flat base throughout the launch. The width of this channel limits the size of missile that can be used. Barnard's record of the maximum diameter of each Ibrim ball enables an estimate to be made of the minimum width of the channel for each shot, and hence the size of the machines used by the garrison. By the above formula the size of machine for every weight of shot can be calculated. However, to apply this rule rigidly to the enormous variety of Ibrim shot weights would result in a ridiculously large number of machines. It has long been obvious that each *ballista* was designed for a shot of a certain weight and maximum



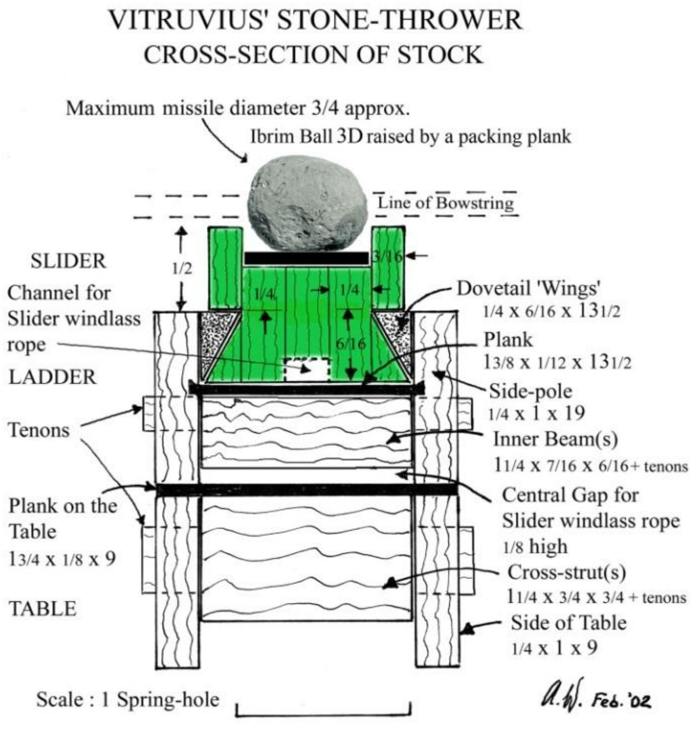


Fig. 21 : Realisation by Len of my interpretation of the cross-section of Table, Ladder and Slider. Note (left) the bracket and spindle holding the pulley wheel feeding the windlass rope from the Central Gap under the Ladder's Inner Beams to the channel in the base of the Slider.

diameter, but that it was sometimes required to launch stones of lesser diameters. These balls would have to be raised to allow the bowstring to contact them half way up. The solution here proposed is a packing plank to slip onto the base of the slider's channel. Stones of 6, 8, and 9 *librae*, of diameters 12, 14 and 15 cm, are ascribed to Centurion Octavius. A 10 *librae* stone, Ball 2E, is also about 15 cm. Since there is only a maximum of 3 cm difference, I suggest that Octavius was using a 10 *librae* machine, one of the standard sizes on Vitruvius' list, with a packing plank 1.5 cm thick to raise the 6 *librae* missile.

As the cross-section (figure 21) shows, the bottom section of the Slider is in the form of a male dovetail which slides along a female groove formed by the two *pterygomata* (dovetail-section "wings") in the top of the Ladder. They are cut from the same piece of wood which supplies the male dovetail of the Slider. Make the cuts at an angle of about 60 degrees. This sliding dovetail could jam in heavy rain or if the wood warps. I have always made sliders loose fitting and as a laminate of several sections of hardwood. The illustration in the mss of the *cheiroballistra* and the surviving wood of the stock on the Xanten bolt-shooter confirm this use of the sliding dovetail.

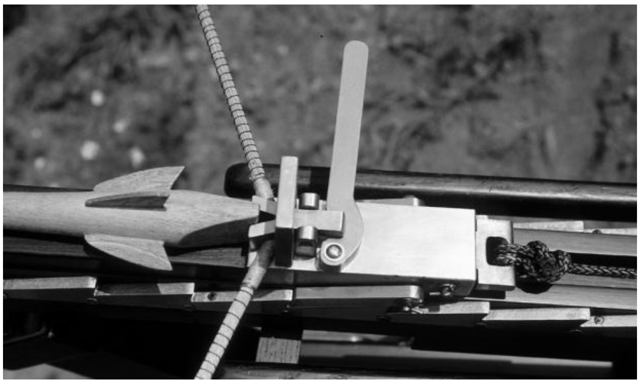


Fig. 22 : Interpretation of the mss figures of the trigger mechanism of the bolt-shooting *cheiroballistra*. The double pronged Claw is a metal version of an archer's two fingers on the bowstring. The *ballista*'s single finger fits into the ring on the back of the bowstring belt.

A small central channel must be ploughed out of the bottom of the Slider to accommodate the windlass rope that effects the forward movement of the Slider (Cross-section figure 21 left. It is clearly visible in figure 1 left).

Trigger

Not mentioned by Vitruvius. Heron *Bel*.110-111 discusses the bowstring and trigger. Its single claw fits into the ring on the back of the bowstring belt. The only detailed description of a trigger mechanism is that given for the bolt-shooting *cheiroballistra*. It is mounted on metal plating which caps the end of the slider. Amongst the Hatra finds there was an iron object in the form of a hook with traces of an iron axle, identified by Baatz (Baatz, 1978a, 6) as possibly the claw of a trigger mechanism. Unfortunately this was too heavily corroded to be of any value.

Was the Trigger mechanism incorporated in or added to the length of the Slider? For our reconstruction we have assumed that it was added to it (see Assembly 3 below).

Windlass

quod autem est ad axona, quod appellatur frons transversarius foraminum trium.

As for the ***axon*** *(**axle**) [of the windlass ?], what is termed the width across is* ***three h.***. This sentence must refer to the axle of the windlass, but is a few lines earlier than the reference to the diameter of the axle :

rotundi autem axis diametros aequaliter erit cheles, ad claviculas autem [36]minus parte sexta decuma [K].

“*The diameter of the round axle will put it on a level with the trigger/trigger block (**chele**), but it will be **one sixteenth** less at the pawls (**claviculae**)*”.

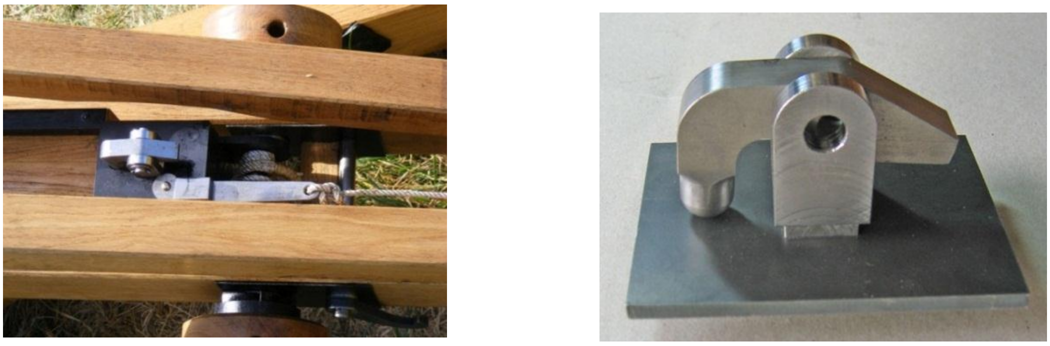


Fig. 23 : (left) Looking down between the two Stays onto the Trigger. Its release lever is in the released position, having been operated by a long rope from several metres behind the catapult for safety reasons. (right) Side view of the Trigger and its mounting plate. (photos : Len Morgan)

Vitruvius’ text uses both the Greek (axon) and Latin (axis) words for axle. The way in which Vitruvius’ mentions the pawls (plural) implies that ratchet wheels were attached to each end of the windlass axle. Heron’s diagram (figure 10) shows a windlass barrel at the rear of the Ladder, and a line of rope on each end of the handspikes. For the larger *ballistae*, this clue and Heron’s extremely important description (*Bel*. 84-6), should be followed and two sets of multiple pulley systems should be made. The doubling up of ratchet and pulley systems allows for one set to hold the Slider if the other breaks, there being no linear side ratchets on this design. This is the design used by Schramm. If the pull-back system fails the catapult will shoot the Slider instead of the missile ! There is sufficient room at the rear of the Ladder for a windlass system because the Ladder is **19** long and the Slider only **12½**.

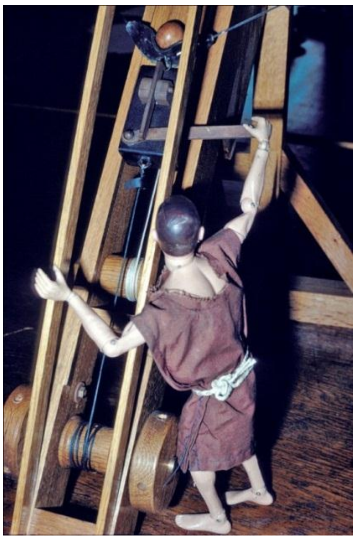


Fig. 24 : Marsden’s model with two windlasses and a demonstration of the trigger release system.

[36] autem <S> minus Schramm-Diels, Marsden.

The windlass described in Heron, with a single loop of rope effecting both forward and backward pulling of the Slider, was adequate for smaller stone-throwers like ours. For the larger stone-throwers Heron recommends the addition of a pulley-system. Heron appears to imply that a single multiple pulley system could work the forward as well as the backward pulling of the Slider. Marsden is right (1971, 49 note 21) to point out that this would not work. On his model a second windlass is used to pull the Slider forward (figure 24).

There is good evidence about Graeco-Roman multiple pulley systems, from Vitruvius, Heron and from archaeology, notably the treadmill crane on the Haterii relief in the Vatican Museum. A little known drawing in Athenaeus Mechanicus of a Ram is useful, and actual pulley blocks survive, e.g. from Kenchreae and the Nemi ships (all in figure 25 below). If we match the five Hatra "sturdy bronze rollers with iron axles" recorded by Baatz 1978a, 6) with Heron's words about a multiple pulley system, we can tentatively suggest that the Hatra stone-thrower employed a single rope passing through two pulley blocks, a triple-pulley attached to the back of the

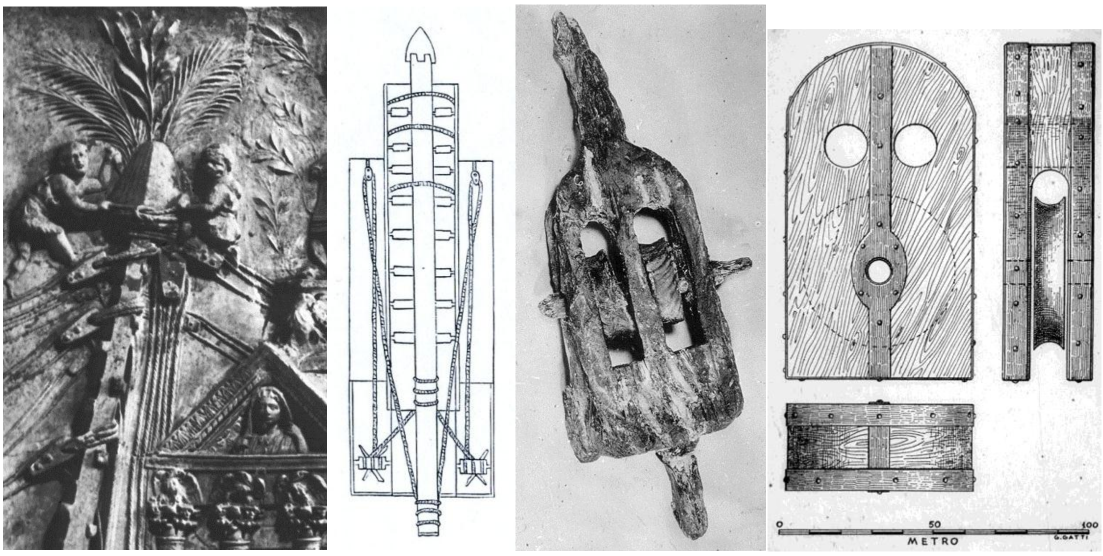


Fig. 25 : Pulley blocks (left to right) : Haterii relief, Athenaeus' Ram, Kenchreae, Nemi.

Slider and a double-pulley fastened at the rear next to the windlass. The Hatra machine was equipped with 16 cm diameter springs and probably shot a missile weighing no more than 4 librae = 1.3 kg = 2.9 lbs. We would obviously need to devise a pull-back with at least a 5 to 1 advantage if we wanted to cope with a shot weighing 80 librae (= 1 talent = 26 kg = 57 lbs), as used by Vespasian at the sieges of Jotapata and Jerusalem, and in the BBC programme "Building the Impossible".

ASSEMBLY 3 : THE SLIDER

The trigger is fastened securely to the rear end of the Slider. For the purpose of our present reconstruction I have assumed that the length of 12½ for the Slider is the length of the missile groove, and that we add an additional 1 to the Slider for mounting the Trigger mechanism. The end of the *cheiroballistra*'s Slider (figure 21) should be examined for one possible way in which the windlass ropes may be attached to the Slider. On my model the pull-back rope is linked to a strong vertical plate slotted into the end of the Slider (figure 18).

ASSEMBLY 4 : THE LADDER, TABLE, LOCKING BAR AND STAYS

It is obvious that the sources do not give all the information needed to construct the Ladder with its windlass, or the Table, and that they say nothing about the methods of joining them to each other. Any reconstruction must attempt to provide solutions based on known Roman engineering practice using components such as T- and H-clamps, metal pins or strapping, wooden draw-tongues etc..

THE ARMS

brachii longitudo foraminum VII[37], crassitudo in radice foraminis <SΓ>[38], in extremis *F*[39].

The **bracchium** (**arm**) *is **7# h.** long, its thickness at the bottom is <**11/16**>[40] **h.**, at the ends **6/16** **h.**.*

The figure for the length of the arms in the Harleian ms is **V.I.** , clearly corrupt. The final full stop can be explained as normal practice, separating the letter-numeral from the following text, but the first stop is unnecessary. Philon gives a length of **6.** But his half springs are drawn from a different rhombus diagram from that of Vitruvius and Heron. Philon's Half-springs are narrower and his spring holes are closer together resulting in a smaller arc of travel for his arms. Remember that Vitruvius' rope-springs were fatter because of his Washer design, and therefore needed wider Half-springs to provide the extra clearance between rope-springs and stanchions.

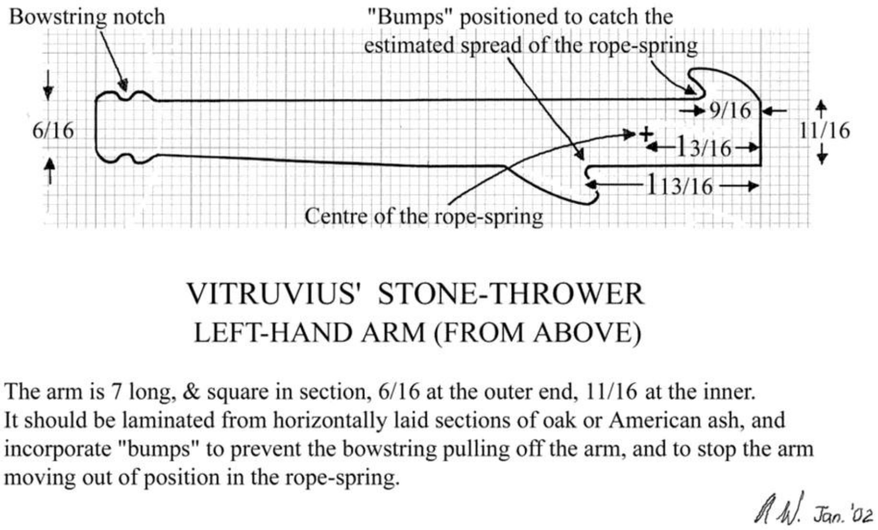


Fig. 26 : My first drawing of the Arm's profile. Len has modified the profiles of the "bumps" for the Mk II machine,

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37 .V.I. H . Gap in other mss. See commentary.

38 foraminis in extremis mss ; ΓZ Schramm-Diels, Marsden. (S is possible by dittography and it is Philon's measurement. But a compound of S such as SΓ is also possible palaeographically and is more likely with 7F arms. See commentary.)

39 F mss. *F* Schramm-Diels, Marsden.

40 Measurement missing in mss. Might be S (1/2) , the figure given by Philon and the last letter of the previous word, or a compound of S such as SΓ (11/16).

I assembled my model's Half-springs, Table and Ladder, and inserted a temporary bowstring and arms 6 long. They were too short to permit the Slider to be fully pulled back. Arms 7 long worked well. Similar testing for the massive BBC *ballista* gave the same result. This is, of course, the length of the arm of the Vitruvian bolt-shooter. Therefore I believe that Vitruvius original figure here was probably **VII**, the first ms stop being a corruption of an **I**. Experiments showed that fitting an 8 long arm with its longer bowstring would place the trigger position so far back that it would leave inadequate room for the windlass and pulley system.

Philon's instruction to "*make the width ½, and the thickness the same*" provides an answer to the question of whether the arms were round or square in section. Vitruvius does not mention curvature, as he does for the bolt-shooter, so presumably they are straight, as one might expect. (The bolt-shooter's spring-frame is euthytone not palintone, i.e. the stanchions are not offset, so that curving its arms is the way to increase arm travel.)

Vitruvius' figure for the thickness of the outer end of the arms is 6/16. Unfortunately his measurement for the inner end has disappeared, probably because the letter numeral in question was similar to the adjacent letters of the words on either side.

Since Philon's shorter arms had a thickness of ½, it is reasonable to assume that Vitruvius' arms would need to be thicker than that at their inner ends. The missing figure was almost certainly SΓ = ½ + 3/16 = 11/16, or S*F* = ½ + 6/16 = 14/16. The latter may turn out to be too thick, have an excessive weight penalty, and cause the rope-springs to scrape the stanchions. Whichever figure is chosen, this inner thickness should be maintained beyond the point where the arm emerges from the rope-spring, the point of maximum stress.. In other words tapering should only begin in the outer half of the arm (figure 26).

From our experience with the bolt-shooter, and that of Payne-Gallwey (P-G, *1907*, 285-7) with his seven foot onager arm, we suggest that for safety the arms should be laminated from kiln- or air-dried horizontal strips of oak or American ash glued with Cascamite. (Glue is not effective with green timber). No arm breaks have been experienced with this method. Some means must be devised of stopping the arms pushing too far into the rope springs and the bowstring slipping off the ends of the arms. We have added projecting bumps to the profile of the laminated strips. Len has modified the profile after his experience with the Mk I build of the machine.

Fig. 27 : Starting to shape the huge arm for the BBC's One Talent (26 kg) *ballista*, using horizontally laminated ash.

THE STAND

basis, quae appellatur εσχαρα, longitudo foraminum <VIII>[41], antibasis foraminum IIII, utriusque crassitudo et latitudo foraminis. compingitur autem dimidio altitudinis [K] columna[42], latitudo et crassitudo IS[43]. altitudo autem non habet foraminis proportionem, sed erit quod opus erit ad usum.

The ***base****, which is called* **εσχαρα** [**eschara** = platform], *is <**8**>* ***h.*** *long, the* ***antibasis (counter-stay)*** ***4 h.*** *; the thickness and width of both are* ***one hole.*** *The* **columna** (**column**) *is fastened together / rigidly connected at half its height; its width and thickness are* ***11/2 h.****. However its height is not calculated in* ***spring-holes****, but will be as practicality dictates.*

Vitruvius uses far fewer words to describe the *ballista* stand than for the tripod stand of the bolt-shooter. The enormous weight of the stone-thrower demands a heavy-duty support: Philon says that the plating alone on a correctly plated machine weighs 25 times the weight of the stone shot.

I have already argued (Wilkins, 2003, 59) that the type of stand seen from the front on Trajan's Column and from the side on the Cupid Gem was that used for palintone catapults.

With Marsden (1971, 205) I assume that there was a universal joint as on the bolt-shooter, possibly achieved by a swivelling block, pinned through the Table's Side-poles (figure 28).

Note Vitruvius' figure of 1½ for the width and thickness of the hefty main support column, presumably square in section, and compare it with the ¾ width and thickness for his far lighter bolt-shooter with its smaller hexagonal cross-section. Having made a convincing suggestion (my text footnote 41) for the missing length of the base, Schramm and Diels then altered the text describing the column from singular to plural to create twin support columns. They then proceeded to change the figure found in all mss for the width and thickness of the column from 1S (1½) to S (½). Most subsequent reconstructions and drawings, including Marsden's, have accepted this design, which does not make a lot of engineering sense: there is a certain irony in that their twin columns end up merged into one at the top. Presumably what led Schramm and Diels to this twin support idea is the phrase *columna compingitur*, which can be translated as "the column is pinned together" and so lead to the thought that only two columns can be "pinned together". But the prefix *com-* is also regularly used simply to strengthen a verb, making the suggested translation just as likely: "the column is securely fastened" or "joined up", as it is to two 45˚ struts on Trajan's Column casts 163-4 (figure 29a), 165, 166 and 169, all depicting a single column on a ground base with 45˚ struts.

Schramm and Diels were rightly concerned that there should be a stand capable of supporting the stone-thrower's weight; but according to Vitruvius' text as transmitted, the single support column's thickness has indeed been massively increased over that of the bolt-shooting *catapulta*. Schramm and Diels' extra struts with ground-bases to front and rear of the column are not in Vitruvius' text. My

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[41] No numeral in mss. VIII Schramm-Diels, Marsden. Possibly correct - the error may have been caused by the similarity of VIII to VM , the last two letters of the previous word.

[42] compingitur autem dimidia altitudinis columna mss ; compinguntur autem dimidio altitudinis columnae Schramm-Diels, Marsden (see commentary).

[43] I S mss ; S Schramm-Diels, Marsden.

belief is that Vitruvius does not mention such detail because the stand for a palintone stone-thrower was of Trajan's Column design, with back support struts as recorded on the Cupid Gem (figure 29b below).

This simple design of stand works well in practice. Its great advantage is that, unlike Vitruvius' effective but awkward tripod stand for the bolt-shooter, it can be dismantled and carried flat. Len has also found that it enables the whole machine at this smallest 2 *librae* size to be tilted forward on its face to allow the catapult to be separated from its base at the start of dismantling.

Fig. 28 : Details of the Stand and Universal Joint.

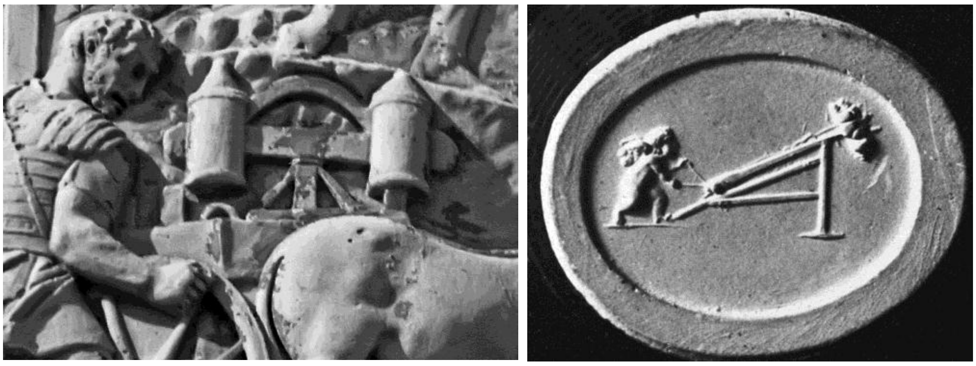

Fig. 29 : (a) Trajan's Column Scene LXVI, Casts 163-4, showing a stand's column and base with 45° struts. (b) The cast of the Cupid Gem, showing the back struts of a stand (photo: D. Baatz).

PHOTOGRAPHS

All photographs were taken by the writer, unless otherwise specified.

APPENDIX 1: Heron’s Belopoiika 99, 4 - 100

This is a key passage to understanding Heron’s Tenons (τορμοι).

Νοεισθω οὐν ἐντεταμενα, ὡς εἰρηται, τα δυο ἡμιτονια, και κειμενα ἐπι τινων κανονων, και ἀφεστωτα ἀπ’ἀλληλων μικρῳ μειζον διπλασιον το του ἑνος ἀγκωνος μηκος. νοεισθω δε τα κατω περιτρητα των ἡμιτονιων τα ΑΒΓΔ, ΕΖΗΘ, τορμους ἐχοντα ἐξ αὐτων τους ΚΛΜΝΞΟΠΡ, συνεχομενα ὑπο κανονων ΣΤΥΦ, ἐν οἱς εἰσιν οἱ τορμοι. και ἀνω δε τα αὐτα ἐπινοειν δει. οἱ δε κατω κανονες και διαπηγμασι συνεχονται πλειοσιν ὡσπερ τοις ΧΦΨΩ, και ἐπι ταδε διαπηγματα σανις ἐπιτιθεται ἀναπληρουσα παντα τον μεταξυ των κανονων τοπον. καλειται δε το πηγμα το συγκειμενον ἐκ τε των κανονων και των διαπηγματων και της σανιδος τραπεζα. οὑτως δε ταθεντων των ἡμιτονιων και των ἀγκωνων εἰς το ἐκτος ἀναπεπτωκοτων ....

Half-spring tenons and Crossbeams.

So imagine the two Half-springs armed as has been described, positioned against certain boards [i.e. the sides of the Table], *and spaced apart from one another by slightly more than double the length of one arm. Imagine the Half-springs’ lower Hole-carriers ΑΒΓΔ, ΕΖΗΘ having tenons ΚΛΜΝ, ΞΟΠΡ protruding from them, and linked by boards ΣΤ, ΥΦ* [Crossbeams] *in which the tenons are inserted. You must contrive the same system for the upper parts.*

Components of the Table.

The lower boards [i.e. the sides of the Table] *are joined by several cross-struts such as ΧΦΨΩ, and on these cross-struts are placed a plank which fills the whole space between the boards. The whole assembly of boards, cross-struts and plank is called the Table. When the Half-springs are armed and the Arms recoil outwards*… [Heron ends by saying that you must pull back the bowstring, position the missile and release the trigger].

This is a very clear explanation of the Crossbeams’ contact with the Table, the eight tenons projecting from them, and the construction of the Table itself.

The opening sentence describes the two Half-springs as *positioned in contact with* (επι epi) *certain boards*. The addition of τινων (tinon) “*certain*” means that these are particular boards, ones that have not yet been described or labelled. They are described a line or two below as the boards which are the sides of the Table. What Heron seems to be saying is that if you take both fully armed Half-springs and space them apart by a certain distance, they will be ready to accommodate the Table and sit flush with its side boards.

However, as editors have spotted, there is an obvious problem with the phrase about the spacing between the two Half-springs as *slightly more than double the length of one arm*, which calculates as more than 14h., when they are only separated by the width of the Table which is 13/4 h. Both Schramm-Diels and Marsden spotted that Philon (*Bel*. 54.1) gives the length of the bowstring as 2.1 times the length of one arm.

Marsden (1971, 54 note 31) continues, "Therefore, what Heron intended to convey was something like this : '…and resting on boards, and such a distance apart that *the ends of the arms* are a little further apart from one another than twice the length of one arm'."

It is quite possible, of course, that the words *the ends of the arms*, which the neuter plural participle αφεστωτα (aphestota = *spaced apart*) might originally have described, have dropped out of the mss. The Greek for *the ends of the arms* would be τα των αγκονων ακρα, also neuter plural.

As mentioned on pp. 13-14, it is very surprising that there is no mention in Heron's text of the Crossbars, clearly drawn and labelled (διαπηξ diapex) on his diagram. Again, this could have been lost by copyists.

APPENDIX 2

I believe that there is a strong case to be made for emending the text of Philon's description of the counter-plate / support-plate (υποθημα hypothema = literally "*placed underneath*") in his *Bel*.54. The reading of the mss describes it as "*under the hole-carrier*" (υπο το περιτρητον hupo to peritreton) and ¼ h. thick. The phrase *under the hole-carrier* implies that it is somehow supporting the hole-carrier from below in the space occupied by the rope-spring, and not positioned between the washer and hole-carrier, as Heron describes it (*Bel.* 97), and as is the actual support-plate under the Hatra washer (figure 6). Philon's text could be emended to υπερ του περιτρητου (hyper tou peritretou) "*on top of the hole-carrier*", an easy correction palaeographically.

I have added these thick Philon support-plates under the washers of my model (figure 18). However, because they are not mentioned by Vitruvius we have omitted them from our reconstruction.

BIBLIOGRAPHY

BAATZ 1978a: Baatz, D. "Recent Finds of Ancient Artillery", *Britannia* IX, 1-17.
BAATZ 1978b: Baatz, D. "Das Torsiongeschütze von Hatra", *Antike Welt* 4, 50-7.
CLEPHAN 1903: Clephan, R.C. "Notes on Roman and Medieval Engines etc.", *Archaeologia Aeliana* 24, 69-114.
Journal of Roman Military Equipment Studies = JRMES (Oxford).
MARSDEN 1971: Marsden, E.W. *Greek and Roman Artillery. Technical Treatises* (Oxford). Reprinted 1999 by Sandpiper.
PAYNE-GALLWEY 1907: *The Crossbow etc.* (London).

SCHRAMM 1917: Schramm, E. “Erläuterung der Geschützbeschreibung bei Vitruvius X 10-12, *Sitzungberichte der königlich preussischen Akademie der Wissenschaften,* phil.-hist. Klasse, LI, 1917, 718 – 734.

SCHRAMM 1918/1980: Schramm, E. *Die antiken geschütze der Saalburg* (Berlin). Reprinted 1980 with an introduction by D. Baatz (Bad Homburg).

WESCHER 1867: Wescher, C. (ed) *La Poliorcétique des Grecs* (Paris).

WILKINS 2003: Wilkins, A. *Roman Artillery* (Princes Risborough).

WILKINS, ROSE & BARNARD 2006: Wilkins, A. Rose, P.J. and Barnard, H. “Roman Artillery Balls from Qasr Ibrim, Egypt” *Sudan & Nubia* Bulletin 10, 2006, 66-80.