The Traction Trebuchet: A Reconstruction of an Early Medieval Siege Engine

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> Trebuchets are machine[s] invented by unbelieving devils. [MARDÎ AL-TARSÛSÎ, A.D. 1187]

Traction trebuchets were medieval rotating-beam siege engines;[1] they were powered by a human team pulling ropes and hurled stone projectiles from a sling. Traction trebuchets were entirely unlike ancient Greek and Roman torsion engines which used springs made of skeins of twisted sinew or hair, and they were quite unlike the later medieval trebuchets whose rotating beams were turned by large counterweights. Counterweight trebuchets were the dominant medieval siege artillery, but the survival of useful Roman-style torsion artillery into the Middle Ages is a myth with Renaissance origins. This myth, as well as confusion with counterweight machines, has hampered our understanding of traction trebuchets so much that some have even questioned their existence. I have reconstructed and tested a full-sized traction trebuchet in order to find out exactly how they worked and how they differed from other kinds of mechanical siege artillery.

Why the Traction Trebuchet Fell into Obscurity

The historiography of the traction trebuchet is inextricably linked to the contributions of centuries of antiquarians and scholars who have wrestled with difficult sources and baffling terminology.[2] The Renaissance, enchanted with the recovery of ancient texts and knowledge,

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[1]Key terms are explained in the Appendix.

[2]Brian Stock puts it in a nutshell when he writes: "The Renaissance invented the Middle Ages in order to define itself; the Enlightenment perpetuated them in order to admire itself; and the Romantics revived them in order to escape from themselves" (Brian Stock, *Listening for the Text: On the Uses of the Past* [Baltimore, 1990], p. 69).

0040-165X/95/3601-0006$01.00

fostered the lingering notion that all things Roman were perfect. The Romans had siege engines; therefore the Romans had the best siege engines imaginable. The flourishing Renaissance mechanical tradition produced "theatres of machines" and similar works by authors such as Konrad Kyeser, Mariano Taccola, and Agostino Ramelli, including the celebrated sketches of Leonardo da Vinci. These works first circulated in manuscript form and later achieved wide distribution through printing. They typically included drawings of fictitious machines which were later confused with real ones, greatly compounding the usual problems of distinguishing image from reality. Drawings of "ancient" siege engines, based on fragments of ancient descriptions fleshed out with artful ingenuity, usually conveyed mechanical cleverness and originality, rather than the details of any sort of living tradition.[3]

The Enlightenment inherited the twin ideas that the Romans had routinely employed devastating siege engines and that all medieval techniques were retrograde by definition. The popularity of the study of war as a suitable preoccupation for civilized gentlemen ensured that misapprehensions about siege machines became firmly rooted. Editions of authors such as Polybius[4] were illustrated with engravings showing catapults and other devices based not on Greek or Roman primary sources but on the best (and often highly fanciful) guesses of the Renaissance. In the Romantic era, there was little difference between scholarly and popular interpretations of the Middle Ages.[5] As Brian Stock put it, "To the Enlightenment, the Middle Ages were primarily a period[, but] for the Romantics, writing roughly a century later, they were also a state of mind."[6] The Middle Ages were seen as a time long before the English Civil War and the French Revolution, characterized by the stability, tranquillity, and obligation which were so much missed in the 19th century.[7] This intellectual context informed 19th-century

[3]Conversely, Renaissance illustrations of counterweight trebuchets are sometimes excellent. For example, Konrad Kyeser's *Bellifortis*, ca. 1405, Göttingen, Universitäts-bibliothek, Cod. phil. 63, ed. G. Quarg (Düsseldorf, 1967), contains a detailed and perfectly credible illustration of a counterweight trebuchet.

[4]Sir Ralph Payne-Gallwey, *The Projectile Throwing Engines of the Ancients* (London, 1907), for example, reproduces many of these engravings, citing an edition of 1727.

[5]Nowhere is this more apparent than in the works of A. W. Pugin. Although Pugin himself, so far as I know, did not say much about medieval artillery, his work set the tone for many who did. See, e.g., Nigel Yates, "Pugin and the Medieval Dream," *History Today* 37 (September 1987): 33 ff.

[6]Stock, p. 64.

[7]See Franklin L. Baumer, *Modern European Thought: Continuity and Change in Ideas, 1600–1950* (New York, 1977); Modris Eksteins, *Rites of Spring: The Great War and the Birth of the Modern Age* (Toronto, 1989); and Stephen Kern, *The Culture of Time and Space, 1880–1918* (Cambridge, Mass., 1983).

scholarship about medieval artillery, including the works of Viollet-le-Duc and Sir Ralph Payne-Gallwey.

Viollet-le-Duc's drawings of siege engines have been uncritically reproduced in many secondary sources. Unfortunately, his lengthy and detailed historical and theoretical explanations never accompany the illustrations. Although he has often been criticized for going beyond the evidence available to him, "in an age of historical revivals, his reconstructions were enthusiastically received."[8] The occasional flagrant misinterpretations in his drawings are not the products of carelessness or stupidity, but of his valiant efforts to reconcile conflicting manuscript evidence. Sometimes this could only be done by verging on mechanical absurdity. For Viollet-le-Duc, all trebuchets had counterweights, and the big distinction was between fixed and swinging weights, rather than between manpowered and counterweight machines.[9] Viollet-le-Duc called those trebuchets with fixed counterweights *mangonels.* He reasoned that since all trebuchets, including *mangonels,* had ponderous counterweights, and there are clearly accounts of crews pulling on the arms of *mangonels* to give impetus to the shot, then some *mangonels* must have had crews *in addition* to their counterweights. Payne-Gallwey's criticism of this idea has discredited the traction trebuchet as a real historical phenomenon.

For English-speaking readers, the works of Payne-Gallwey are the most accessible source of technical detail on pre-gunpowder artillery.[10] Payne-Gallwey reproduced many illustrations dating back to Renaissance woodcuts, including, for example, the drawing of the huge stonebow by Leonardo da Vinci. Troubled by the plausibility of Leonardo's machine, Payne-Gallwey quoted a lofty appraisal of Leonardo's technical insight and concluded that Leonardo's drawings were "fairly correct."[11] In spite of such instances of what his detractors have called downright shoddy scholarship, Payne-Gallwey reconstructed a variety of ancient torsion weapons and published the results of his experiments. He thought very

[8]Viollet-le-Duc, *Annals of a Fortress,* trans. Benjamin Bucknall (London, 1983; first published 1874; first English-language edition, London, 1875), p. viii. Much of Viollet-le-Duc's work was actually a thinly veiled call to fortify against impending Prussian attack.

[9]Viollet-le-Duc, *Dictionnaire raisonné de l'architecture française du XI^e^ au XVI^e^ siècle* (Paris, 1875), 5:220.

[10]Payne-Gallwey, *Projectile Throwing Engines* (n. 4 above), and *The Crossbow, Medieval and Modern, Military and Sporting: Its Construction, History and Management, with a Treatise on the Balista and Catapult of the Ancients and an Appendix on the Catapult, Balista and the Turkish Bow* (New York, 1903).

[11]"'No artist before his time ever had such comprehensive talents, such profound skill or so discerning a judgement to explore the depths of every art of science to which he applied himself.—John Gould, *Dictionary of Painters,* 1839.'" See Payne-Gallwey, *Projectile Throwing Engines* (n. 4 above), p. 26, fig. 17.

highly of these engines: "If the knowledge of constructing the great catapult of the ancients in its original perfection had been retained, such a clumsy engine as the medieval trebuchet would never have gained popularity. . . . It is certain that if the latter kind of engine had survived in its perfect state the introduction of cannon would have been considerably delayed, for the effects in warfare of the early cannon were for a long period decidedly inferior to those of the best projectile engines of the ancients."[12] Payne-Gallwey expressed confidence that he "could now build an engine of a size and power to accomplish such a feat [i.e., shooting 700 or 800 yards] if light missiles were used and if its cost were not a consideration."[13] Unfortunately, there has never been a time when cost was not a consideration, and the economic implications of highly complex artillery cannot be lightly dismissed. Payne-Gallwey also failed to consider the historical availability of materials and skilled craftsmen: his machines depended on the use of industrially manufactured components such as cast-iron ratchets, pawls, and gears which he ordered from a foundry. Although he has been criticized for being cheerfully oblivious to such concerns, his work has nevertheless been a valuable foundation for subsequent research.

Modern efforts to sort out the manuscript evidence and reconstruct ancient engines have benefited tremendously from conditions unavailable to medieval artificers. The low cost of strong materials in the wake of the Industrial Revolution and the ease of information circulation afforded by the printing press have made it possible to reestablish a craft tradition and to publish both archaeological finds and experimental results. The first authentic reconstructions of ancient artillery were made by Erwin Schramm during the First World War.[14] His work was based on Greek and Roman reliefs and archaeological evidence as well as texts.[15] Making use of all these resources, E. W. Marsden has written the definitive study of ancient artillery, collecting, translating, and commenting on every major text.[16] No comparable study of medieval siege weapons exists.[17]

No torsion artillery of significant military value survived the collapse of the Roman Empire because the means to produce and maintain it

[12]Ibid., pp. 7–8.

[13]Ibid., p. 10.

[14]Erwin Schramm, *Die antiken Geschütze der Saalburg* (1918; Bad Homburg vor der Höhe, 1980).

[15]See Dietwulf Baatz, "Recent Finds of Ancient Artillery," *Britannia* 9 (1978): 1–17.

[16]E. W. Marsden, *Greek and Roman Artillery: Historical Development* (Oxford, 1969), and *Greek and Roman Artillery: Technical Treatises* (Oxford, 1971).

[17]This is in part because the sources are relatively more abundant and diverse. A recent and comprehensive survey of the field, however, can be found in Kelly DeVries's *Medieval Military Technology* (Peterborough, Ont., 1992).

became unavailable.[18] Roman catapults existed not only as isolated artifacts but also as the products of a vast array of mutually interacting social, economic, and political forces: Roman torsion artillery was part of the Roman "technological system."[19] Marsden described elements of the extensive infrastructure of this system, which depended on the maintenance of arsenals, such as those at "Pergamum, Rhodes, and Alexandria, all with long traditions of craftsmanship and capable of satisfying the needs of their states in every foreseeable circumstance."[20] When Rome lacked sufficient arsenals and centralized production and maintenance facilities in the Republican period, it also experienced a shortage of artillery. In the early Imperial period, with an army of hundreds of thousands of long-term professionals on regular payroll, legions could afford to maintain the experts, workshops, and traditions of craftsmanship required to produce torsion artillery and any other military equipment they required.[21]

But by the late 3d century, a shortage of good artificers once again seriously hampered attempts to produce and deploy torsion artillery. The simpler, one-armed onager became the standard piece of heavy artillery as early as the 2d century, as well as the *arcuballista,* which Marsden identifies as a nontorsion device.[22] "The artillery legionaries of the fourth century could no doubt maintain their machines in efficient working order, but they were constructed and given major overhauls in imperial workshops (*fabricae ballistariae*)."[23] Only in such workshops could the army maintain the materiel and trained men necessary to produce effective torsion weapons. No such workshops were perpetuated by the barbarians who overran the western Empire.[24]

Although full-sized torsion engines are inherently dangerous, it is not difficult to produce a little one that can toss a small projectile a fair

[18] I offer my interpretation to vie with the many others. Caroll M. Gillmor, "The Introduction of the Traction Trebuchet into the Latin West," VIATOR: *Medieval and Renaissance Studies* 12 (1981): 1, n. 1, cites the following German literature: Erich Sander, "Der Verfall der römischen Belagerungskunst," *Historische Zeitschrift* 149 (1934): 457–67, and "Der Belagerungskrieg im Mittelalter," *Historische Zeitschrift* 165 (1942): 99–110; Friedrich Lammert, "Die antike Poliorketik und ihr Weiterwirken," *Klio* 31 (1938): 389–411; and W. Gohlke, "Das Geschützwesen des Altertums und des Mittelalters," *Zeitschrift für historische Waffen- und Kosstümkunde* 5 (1909–11): 379–80.

[19] See Wiebe E. Bijker, Thomas P. Hughes, and Trevor J. Pinch, eds., *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology* (Cambridge, Mass., 1987), for a description of "technological systems."

[20] Marsden, *Historical Development,* p. 175.

[21] Ibid., pp. 183 ff.

[22] Ibid., p. 195. The *arcuballista* may have been some kind of crossbow which ultimately gives us the French word *arbalète.*

[23] Ibid., p. 197.

[24] Philippe Contamine, *War in the Middle Ages,* trans. Michael Jones (Oxford, 1984; first published as *La guerre au Moyen Âge,* Paris, 1980), p. 11.

distance. For example, Jean Sire de Joinville reports that Jean, comte d'Eu, fashioned a "miniature ballistic machine" circa 1253 and used it to throw stones at his table at dinner.[25] In 1284 this same comte d'Eu commissioned the famous poet Jean de Meun to make a vernacular French translation of Vegetius's *De re militari*.[26] It is entirely possible, if somewhat unlikely, that the comte d'Eu made a miniature onager. A full-scale machine, however, is a different matter; if the frame cannot withstand the tremendous forces set up by the torsion skein, or if the slightest error is made handling the loaded machine, the result can be disastrous for the operators. Marsden cites Ammianus Marcellinus, who relates such an accident: "Among these battles, an architect from our side, whose name is not extant, happened to be standing near a 'scorpion' siege-machine when the stone which the operator falteringly put in the sling bounced backwards; [the architect] breathed out his soul falling on his back with a squashed chest with all the structure of his limbs being dismembered so that distinguishing features of the whole body were not even recognizable."[27] Torsion artillery is liable to fail this way because the skeins must move between a high-energy state (tightly stretched to the point of being rock hard) and an even higher-energy state (even more tightly stretched due to being deflected in torsion). If anything goes wrong, there is more than enough energy available to injure or kill anyone struck by the flying pieces or the misdirected missile. Traction artillery, by contrast, is much more forgiving.

If medievals used ancient-style torsion engines of real military value, they must have *re*constructed them either from written or pictorial evidence, since the ancient means of producing them had perished. But neither of these sources could have been adequate. Ancient reliefs of torsion engines, such as Trajan's Column, lack sufficient technical detail to serve as the basis of a reconstruction, although they are very useful in a corroborative capacity. The three most important Latin sources on Roman artillery were Vitruvius, Ammianus Marcellinus, and Vegetius.[28]

[25]Jean Sire de Joinville, *Histoire de Saint Louis par Jean Sire de Joinville, suive du credo et de la lettre à Louis X, texte ramené a l'orthographe des chartes du Sire de Joinville*, ed. M. Natalis de Wailly (Paris, 1868), bk. 113, chap. 390, secs. a–c, pp. 208–9. For English trans., see Jean Sire de Joinville and Geoffroy de Villehardouin, *Chronicles of the Crusades*, trans. M. R. B. Shaw (Harmondsworth, Middlesex, 1963; reprint, 1984), pp. 310–11.

[26]Charles Reginald Shrader, *The Ownership and Distribution of Manuscripts of the* De re Militari *of Flavius Vegetius Renatus before 1300* (New York, 1976), pp. 43, 60–61.

[27]Marsden, *Historical Development* (n. 16 above), p. 260 and n. 3: "Amm[ianus Marcellinus]. xxiv. 4. 28: '*inter haec certamina nostrae partis architectus, cuius nomen non suppetit, post machinam scorpionis forte assistans, reverberato lapide quem artifex titubanter aptaverat fundae, obliso pectore supinatus, profundit animam disiecta compage membrorum, adeo ut ne signa quidem totius corporis noscerentur.*'"

[28]Gillmor (n. 18 above), p. 5.

None of these, given the unillustrated and often fragmentary and corrupt condition of the medieval manuscripts, would have supplied enough specific information to reconstruct useful torsion artillery. The works of the Roman architect and engineer Vitruvius were widely disseminated, but "much of the tenth book, devoted to machinery, is unclear without illustrations and is not always fully understandable with them."[29] There is no evidence of post-Carolingian manuscripts of Vitruvius which were illustrated.[30]

Although Marsden calls Ammianus Marcellinus's description of a ballista "abstruse" and "unhelpful,"[31] he derives its sense in the context of the entire corpus of extant ancient technical literature—a feat of scholarship inconceivable before the printing press. Ammianus Marcellinus's description of an onager is better, but the problem of building one large enough to use in an actual siege grows with the machine. For example, he gives no clues about how to tighten the skein, except to say that it takes eight young stalwarts to haul the arm back after the tightening.

Vegetius's was "the most popular, and thus perhaps the most influential, discussion of the art of war available during the Middle Ages."[32] The book appeared increasingly in the hands of soldiers and political figures from the end of the 10th century onward, and book 4, which dealt with siege warfare, was frequently excerpted.[33] The description of a torsion engine offered by Vegetius is, however, technically useless, amounting to no more than an assurance that the bigger it is, the farther it shoots, and that *if it is handled by experts* it will pierce whatever it hits.[34] In sum, conditions in the medieval Latin West were very strongly stacked against either the perpetuation or the readoption of torsion-powered artillery. In the East, the Byzantines generally conducted their sieges by tunneling under defenses rather than attempting to go through or over them. A Byzantine survival of some form of torsion artillery alongside the traction trebuchet, which was known to them as early as the 6th century, is possible but highly unlikely.[35]

[29]Carol H. Krinsky, "Seventy-Eight Vitruvius Manuscripts," *Journal of the Warburg and Courtauld Institutes* 30 (1967): 37, 41.

[30]Ibid., p. 43.

[31]Marsden, *Technical Treatises* (n. 16 above), pp. 238–39.

[32]Shrader (n. 26 above), p. 161.

[33]Ibid., pp. 157–60. At a siege in the Loire Valley in 1147, for example, Geoffrey Plantagenet used an incendiary bomb which was made by reference to a copy of Vegetius. See Geoffrey Lester, *The Earliest English Translation of Vegetius' De Re Militari,* edited from Oxford MS Bodleian Douce 291, Middle English Texts 21 (Heidelberg, 1988), p. 13.

[34]Marsden, *Technical Treatises,* pp. 236–37 (emphasis mine).

[35]Paul E. Chevedden, "The Artillery Revolution of the Middle Ages: The Impact of the Trebuchet on the Development of Fortifications" (unpublished ms., 1991), pp. 10 ff. Eric

The idea that Roman machines survived into the Middle Ages has persisted partly because of the profusion of interpretations of the term *mangonel* and its etymological relatives. The *mangonel* has been interpreted as almost every type of pregunpowder artillery ever known, from ancient torsion machines to fixed-counterweight trebuchets. In 1871, Colonel Henry Yule pointed out that no medieval engine depended on torsion; there were only great slinging engines and great crossbows.[36] Yule further pointed out that "*mangonel*" may share an etymology with the Arabic "*manjanik,*" and he also correctly distinguished the two main kinds of trebuchets and their differences, that is, that the *mangonel* could be worked more quickly and was made of lighter stuff than the trebuchet proper. Unfortunately, his insights were buried as a ten-page note on a chapter of *The Book of Ser Marco Polo.* Marsden, citing Payne-Gallwey, wrote that the "[one-armed onager] continued in use right through the Middle Ages, when it was known as a catapult or mangonel, until it was partially superseded, in the twelfth century, by the more spectacular *trébuchet.*"[37] Even the recently published and levelheaded treatment of D. J. Cathcart King describes the *mangonel* as a Roman machine surviving into the Middle Ages, although he acknowledges traction trebuchets as well.[38] The proliferation of equivocal references such as these renders the term *mangonel* all but useless without lengthy qualifications.

The superficial similarity between the traction trebuchet and the onager, both single-arm engines with slings, has compounded the confusion. Although it is possible that the term *mangonel* was derived from the Arabic *manjanîq,* Paul Chevedden points out that it is also possible that it shares a common root in the Byzantine Greek word *manganon:* "The derivation of the word *manjanîq,* although it comes from the Byzantine Greek word *manganon,* from the form *manganikon,*

McGeer of Harvard University, in his "Byzantine Siege Technology: Theory and Reality" (paper presented at the Conference on Urban Warfare in the Middle Ages at Pennsylvania State University, April 3–4, 1992), suggested that siege engines of any kind may have been more characteristic of Byzantine military theory than of reality.

[36]Henry Yule, *The Book of Ser Marco Polo, The Venetian, Concerning the Kingdoms and Marvels of the East* (London, 1871), pp. 121–22 and n. 3.

[37]Marsden, *Technical Treatises,* p. 249. Although I accept the body of Marsden's account of the development of Greek and Roman artillery, I reject his further assumption (which, to be fair, is not his mistake alone) that the onager, an expensive, complex, and infrastructure-dependent technology, somehow survived the collapse of the system which produced it and then remained in use for the better part of a millennium without any further development or evolution except that it became known by a new name.

[38]D. J. Cathcart King, *The Castle in England and Wales: An Interpretive History* (Beckenham, Kent, 1988), p. 126. King mentions the oriental origins of traction trebuchets, calling them "*petraria,*" or "*perrière*" (which simply means "rock throwers"), terms which I find more euphonious than "traction trebuchet," but also more ambiguous.

passed into Arabic via Aramaic, the most widely spoken tongue of Sasanian Iraq. The term *'arrâdah* comes from a nearly identical Aramaic form, which is a direct translation of the Greek *onagros* ('wild ass'). Although the Aramaic term may have originally referred to an onager, its Arabic form denotes a small pole-frame traction trebuchet. The term *manjanîq* was used to designate the larger trestle-frame traction trebuchet."[39] If a similar semantic shift occurred in the Latin vocabulary, then we can see why onagers and *mangonels* might have become confused: onager, denoting the one-armed torsion engine, may have been held over as a general term denoting any one-armed engine. A semantic collision with the term *mangonel*, adapted from the Arabic *manjanîq* to denote a traction trebuchet, would have planted the seeds of the enduring inconsistency we observe to this day.[40]

A better understanding of the traction trebuchet will alleviate much of this confusion. The first unambiguous descriptions of this manpowered siege engine can be found in Chinese and other oriental sources.[41] The machine's diffusion via the Arabs and the Islamic peoples and its use by the Byzantines as early as the 6th century have now been

[39]Chevedden, "Artillery Revolution," p. 23.

[40]Nowhere are misconceptions and confusion about siege weapons more in evidence than in Jim Paul's book *Catapult: Harry and I Build a Siege Weapon* (New York, 1991). The following excerpt is representative: "But at the close of the Roman empire, the technology of the catapult, like much classical knowledge, was scrambled or lost in the Dark Ages, and the powerful and exact Roman machines were replaced by cruder forms, the constructions of the people in a fallen time. It was not until the twelfth century that northern Europeans made widespread use of a large siege engine, the clumsy trebuchet, with its long arm and its heavy counterweight—usually a box of stones. Imprecise, immovable, liable to break down and generally stupid, the trebuchet was nonetheless formidable, powerful enough to throw a dead horse over a wall—as a kind of primitive chemical warfare—or, for that matter, to return the head of the hapless emissary of the besieged to his people" (p. 62). A showcase of historical misinformation in this vein, *Catapult* also reproduces indiscriminately a variety of illustrations from Viollet-le-Duc and Payne-Gallwey.

[41]Guitty Azarpay, *Sogdian Painting: The Pictorial Epic in Oriental Art*, with contributions by A. M. Belenitskii, B. I. Marshak, and Mark J. Dresden (Berkeley, Calif., 1981), pp. 64–65, figs. 28, 29; L. Carrington Goodrich and Fêng Chia-shêng, "The Early Development of Firearms in China," *Isis* 36 (1946): 114–23; Frank A. Kierman, Jr., and John K. Fairbank, eds., *Chinese Ways in Warfare* (Cambridge, Mass., 1974); Joseph Needham, "China's Trebuchets, Manned and Counterweighted," in *On Pre-modern Technology and Science: A Volume of Studies in Honor of Lynn White, jr.*, ed. Bert S. Hall and Delno C. West (Malibu, Calif., 1976), pp. 107 ff.; Sergej Aleksandrovič Školjar, "L'artillerie de jet à l'époque Sung," *Études Sung*, ser. 1, *Histoire et institutions* (Paris, 1978), pp. 119–42; E. T. C. Werner, *Chinese Weapons* (Shanghai, 1932); Robin D. S. Yates, "Siege Engines and Late Zhou Military Technology," in *Explorations in the History of Science and Technology in China: A Special Number of the "Collections of Essays on Chinese Literature and History,"* ed. Li Guogao et al. (Shanghai, 1982), pp. 409 ff.

established.[42] The early arrival of the traction trebuchet in the West removes the need to postulate the survival of Roman machines: there was a cheaper, safer, and more effective technology available. In A.D. 597, for example, the Avaro-Slavs used fifty rock throwers at the siege of Thessaloníki. These machines were traction trebuchets. An eyewitness account is given by John, Archbishop of Thessaloníki, in the *Miracula of St. Demetrius:*

> These [*petroboles*] were tetragonal and rested on broader bases, tapering to narrower extremities. Attached to them were thick cylinders well clad in iron at the ends, and there were nailed to them timbers like beams from a large house. These timbers had the slings from the back side and from the front strong ropes, by which, pulling down and releasing the sling, they propel the stones up high and with a loud noise. And on being fired they sent up many great stones so that neither earth nor human constructions could bear the impacts. They also covered those tetragonal *petroboles* with boards on three sides only, so that those inside firing them might not be wounded with arrows by those on the walls. And since one of these, with its boards, had been burned to a char by a flaming arrow, they returned, carrying away the machines. On the following day they again brought these *petroboles* covered with freshly skinned hides and with the boards, and placing them closer to the walls, shooting, they hurled mountains and hills against us. For what else might one term these extremely large stones.[43]

The Vikings besieged Paris with "*mangonels*" in 885–86,[44] and the Magyars used siege engines on August 8, 955, against low stone walls with no towers.[45] By the 12th century, numerous Western chronicles were

[42]See Paul E. Chevedden, "The Citadel of Damascus and al-ʿAdil's New System of Defensive Planning" (Ph.D. diss., University of California, Los Angeles, 1986), "The Use of the Rotating-Beam Siege Machine in the Islamic Conquests" (paper presented at the Twenty-third Middle East Studies Association Conference, Toronto, November 15–18, 1989), and "Artillery Revolution" (n. 35 above); DeVries (n. 17 above), pp. 133–37; Donald R. Hill, "Trebuchets," VIATOR: *Medieval and Renaissance Studies* 4 (1973): 99–116; and Gillmor (n. 18 above).

[43]Chevedden, "Artillery Revolution," p. 11, after Speros Vryonis, Jr., "The Evolution of Slavic Society and the Slavic Invasions in Greece: The First Major Slavic Attack on Thessaloníki, A.D. 597," *Hesperia* 50 (October–December 1981): 384. I agree with Chevedden's substitution of the original Greek *petroboles* ("rock throwers") for Vryonis's translation of this word as "*ballistrae,*" which may leave the incorrect impression that these machines were some kind of torsion catapults.

[44]Contamine (n. 24 above), p. 105; J.-F. Finó, "Machines de jet médiévales," *Gladius* 10 (1972): 28; and Gillmor (n. 18 above), p. 3.

[45]Contamine, p. 35.

giving details about siege warfare although most of them were not generous with their technical descriptions.[46]

A major obstacle to understanding the traction trebuchet has been the spectacular success of its evolutionary descendant, the counterweight trebuchet—the much larger, more powerful, and more accurate (but also slower, more cumbersome, and more expensive) weapon which did not appear until the mid- or late 12th century. Although traction and counterweight trebuchets work on the same general principles, they differ in critical details. The two have been conflated, and characteristics specific to the more recent engine have been attributed to its predecessor.[47] Donald R. Hill discussed the properties of the two machines. His discussion is as thorough as it can be without actual practical experience, as he himself indicates: "Although it is easy to describe the dynamic system of the traction machine, it is impossible to derive a clear idea about its design and performance from theoretical considerations because there are too many unknown factors, notably the resilience of the beam, the tractive force exerted, and the average angle at which it was applied."[48] Furthermore, as J.-F. Finó writes: "The study is complicated by the fact that the engines, built out of wood, have today disappeared entirely, and nothing survives except a few projectiles (and again, one cannot be sure that some among these are not stone cannonballs for primitive gunpowder artillery)."[49]

[46]Some examples which are edited and readily available in English translation include Emily Atwater Babcock, *A History of Deeds Done beyond the Sea, by William, Archbishop of Tyre,* trans. A. C. Krey, 2 vols. (New York, 1943); M. Chibnall, ed. and trans., *The Ecclesiastical History of Oderic Vitalis* (Oxford, 1978); Charles Wendell David, *De Expugnatione Lyxbonensi: The Conquest of Lisbon* (New York, 1936); Galbert of Bruges, *The Murder of Charles the Good,* ed. and trans. James Bruce Ross (Toronto, 1982); Joinville and Villehardouin (n. 25 above); Edward Peters, ed., *The First Crusade: The Chronicle of Fulcher of Chartres and Other Source Materials* (Philadelphia, 1971); K. R. Potter, *Gesta Stephani: The Deeds of Stephen* (London, 1955); and Francis Joseph Tschan, *The Chronicle of the Slavs by Helmold, Priest of Bosau* (New York, 1966). *Oderic Vitalis* is fairly typical in the level of detail provided by 12th-century chroniclers: *"Deinde suis iussit ut preparatas machinas erigerent et ualidos assultus in oppidum darent"* (p. 408). ("Thereupon he commanded his men to raise the siege engines they had prepared and attempt to storm the castle.") Or again, *"sed illos qui in arce clementiam eius obsecrabant aptatis expugnari machinis cogebat"* (p. 540). ("But [the king] built siege engines and prepared to assault the castle while those inside pleaded for mercy.")

[47]For example, Finó, p. 32: *"Cependant, l'adjonction d'un lourd contrepoids dut bientôt apparaître comme essentielle"* ("Nevertheless, the addition of a heavy counterweight must soon have seemed essential").

[48]Hill (n. 42 above), p. 107. One example of this problem is Hill's own assumption (p. 116) that the "sling-release worked in an exactly similar way" on both machines, which turns out to be true only in a general sense.

[49]Finó, p. 25: *"L'étude est rendue délicate par le fait que les engins, construits en bois, sont entièrement disparus aujourd'hui et qu'il n'en subsiste que quelques projectiles (encore faut'il être assuré que certains de ceux-ci ne sont pas des boulets de pierre de l'artillerie à feu primitive)."*

How the Traction Trebuchet Was Reconstructed

A carefully managed reconstruction can provide the necessary missing data and perspectives to shed new light on the available sources.[50] Thus illuminated, the sources often divulge subtler information than they were previously thought to contain. Three levels of experimental archaeology have been distinguished.[51] First, there are simulations which copy the original form of an artifact for the purposes of display, fund-raising, and education; second, there are authentic reproductions using period materials and methods; and third, there are tests of the functions of these copies. Within each of these levels, experimental reproductions may be further classified by aim. Thus, we find everything from all-out efforts to re-create even the precise shop conditions and working hours of the workers, to more limited efforts to reconstruct only *parts* of artifacts in such a way that those parts, being functionally authentic, may be studied. This project can be classified as a first-level reconstruction—a simulation, but a functional, and hence testable, one. My conclusions are based on five years of experience with this kind of machine and a total of six erections of the current machine over a period of three years.[52]

[50]See Jay A. Anderson, "Immaterial Material Culture: The Implications of Experimental Research for Folklife Museums," in *Material Culture Studies in America,* ed. Thomas J. Schlereth (Nashville, 1982), pp. 306–15.

[51]See S. McGrail, "Experimental Boat Archaeology: Some Methodological Considerations," in *Sailing into the Past: Proceedings of the International Seminar on Replicas of Ancient and Medieval Vessels, Roskilde, 1984,* ed. Ole Crumlin-Pedersen and Max Vinner (Roskilde, 1986). See also John Coles, "Experimental Archaeology: Theory and Principles," in *Sources and Techniques in Boat Archaeology: Papers Based on Those Presented to a Symposium at Greenwich in September 1976, Together with Edited Discussion,* ed. Sean McGrail, archaeological ser. no. 1, British Archaeological Reports (BAR) suppl. ser. 29 (Greenwich, 1977); and John Coles, *Experimental Archaeology* (London, 1979).

[52]In the summer of 1988, after frustrating winter-long attempts to build an arrow-shooting torsion ballista, and having been inspired by Randall Rogers at the Twenty-third International Congress on Medieval Studies at Western Michigan University in Kalamazoo (hereafter Medieval Congress in Kalamazoo), I constructed a simple traction trebuchet which could throw a fist-sized rock 120 m. I report this early work, and compare the ballista with the traction trebuchet, in W. Ted Szwejkowski, "The Amateur Artillerist, Basement Ballistics, and Curious Coincidences: On Tinkering with Siege Engines," AVISTA *Forum* 4, no. 1 (Association Villard de Honnecourt for the Interdisciplinary Study of Medieval Technology, Science, and Art, Haverford, Pa., Fall 1989). In the summer of 1989, I built the first version of the machine described here. In July, before the arm was planed down to its tapered form, the machine was tried with an improvised wooden hook in a public park in Etobicoke, a suburb of Toronto. In August, it was tested at Cooper's Lake Campground in Pennsylvania, where a large field beside an archery range was available and where volunteers could be mustered for the trials. And in November, it was displayed in the Toronto Sheraton Centre at the Twenty-third Middle East Studies Association Conference; I thank Wendy Wiener for coordinating our "Sheraton Siege." The first

The most important textual source used in the reconstruction of the machine was the military manual of Mardî b. 'Alî b. Mardî al-Tarsûsî, written around A.D. 1187 for Salâh al-Dîn, entitled *Instruction of the Masters on the Means of Deliverance in Wars from Disasters, and the Unfurling of the Banners of Information: On Equipment and Engines which Aid in Encounters with Enemies.* Al-Tarsûsî discusses a variety of traction trebuchets, distinguishing the Arab, the Turkish, and the Frankish varieties. He discusses their relative strengths and weaknesses, and makes suggestions about what kinds of wood are appropriate and how the wood is to be joined. He provides several schematic illustrations of the various machines, specifies their range, and gives vital practical advice about how to operate them:

> Know, God helps you on the right way to Him. He helps you by appointing you to unveil knowledge and lets you know it [this knowledge], that is, the shooting of trebuchets has secrets which must be acquired and retained, and meanings, which in order to know, the student should acquire all of it to help him reach his goal, so that the sun of knowledge will rise and show all of its sides to him, and [knowledge] will be perceived. Of this knowledge is [the following]:
>
> If the shooter stands directly under the pouch [of the sling], the stone will be very high and [the range] will be short, and it may

round of testing confirmed that the machine worked, but my private funding and reliance on volunteer assistance rendered the results tentative. The machine was completely overhauled during the winter of 1991. In April of that year, it was set up in the Back Campus of the University of Toronto, and testing resumed under the aegis of the Eighth Annual Historic Scientific Experiment of the Institute for the History and Philosophy of Science and Technology. The cosponsors of the "Trebuchet Experiment Day" included the Alumni of the School of Graduate Studies, Victoria College, the Faculty of Applied Science and Engineering, the Centre for Medieval Studies, the Department of Civil Engineering, the Department of Mechanical Engineering, the Department of Middle East and Islamic Studies, University College, and the Graduate Students' Union, all of the University of Toronto. Jeff Coatsworth, Bert Hall, Wilf Locket, and Connie Gardner deserve a special note of thanks. Once again, the crews and assistants were volunteers, but they were systematically organized in light of what had been learned in the previous round of testing, and we recorded precise observations. One month later, in May, the machine was demonstrated at the Twenty-sixth Medieval Congress in Kalamazoo. My thanks to the people who made that demonstration possible: Don Kagay who organized the special session and demonstration, Otto Gründler who allowed it all to happen, and Kathryn Woodruff who acted as liaison. Refitted with a new arm and hook, the machine was shown for the last time one year later, in April 1992, at the conference on The Medieval City under Siege at Pennsylvania State University. I would like to thank Vickie L. Ziegler of Penn State for organizing the conference, Professor McNeil and the engineering students for helping to set up and being an enthusiastic crew, and most particularly William Leech of the Pennsylvania Military Museum in Boalsburg for hosting the demonstration itself and for personally standing the night watch over the machine to ensure its security.

possibly fall on [B132v/A96v] the men [i.e., the pulling crew]. If [the shooter] moves out from the pouch toward the end of the beam by a distance of one span [of a hand = 22–24 cm], the launch will be farther. The most one should move out from the beam is two spans [44–48 cm], [and] no more, for, if one goes beyond this, the launch will be short. The longest distance which the stone can reach is 60 *bâ‘* [ca. 120 m], and the shortest is 40 *bâ‘* [ca. 80 m]. Another principle which determines the farness or the shortness of the distance [of the shot] is the flexibility or dryness of the beam. When the beam is flexible, but not excessively so, it has a farther range and is more effective. When it is dry, it is less so. The shooter should have his feet wide apart, grasp the pouch with his hands, and sit down while he pulls the pouch each time [B136r]. The best and most proper wood to make the beam is cherry wood. If there is none of this kind, it must be of a closely-knotted wood of intermediate [quality] such as cedar or the like.[53]

Unfortunately, al-Tarsûsî's illustrations of the frame of the machine are so schematic that unless one knows what the finished product is supposed to look like, they can be more confusing than helpful. For this reason, I chose to build what he would have called a Frankish trebuchet, since a number of European manuscripts clearly show such machines. They are characterized by a triangular frame built onto the butt end of the rotating beam.[54] Most of the manuscript illustrations I consulted featured whole-number ratio divisions of the beam by the axle. The ratio, however, varied from text to text. I determined the ratio of my beam by following al-Tarsûsî's overall ratio of six to one, but I adjusted the internal ratios of the triangular frame on the beam in accordance

[53]Mardî b. ‘Alî b. Mardî al-Tarsûsî, *Tabsirat arbâb al-albâb fî kayfîyat al-najâh fî al-hurûb min al-aswâ' wa-nashr a‘lâm al-i‘lâm fî al-‘udad wa-al-âlât al-mu‘înah ‘alá ligâ' al-a‘dâ'*. The main MS ("B") is in the Bodleian Library at Oxford, Huntington Collection, no. 264, with a second MS ("A"), copied by Mugammad c. Salmân in A.D. 1388, in the Süleymaniye Library in Istanbul, MS 2848 mũ, Ayasofya Collection. Paul Chevedden provided me with his own translations of portions of these manuscripts after the Twenty-fourth Medieval Congress in Kalamazoo in 1989. Without Dr. Chevedden's generous collaboration, this project would have been inconceivable.

[54]See, inter alia: *Annales janueses*, "events of 1182" (13th century, Italy, MS suppl. lat. 773, fol. 107r, Bibliothèque Nationale [BN], Paris), in Jaroslav Folda, *Crusader Manuscript Illumination at Saint-Jean d'Acre, 1275–1291* (Princeton, N.J., 1975); William of Tyre, *History of Outremer*, "the siege of Nicaea," pl. 154 f (mid-13th century, Manuscrit français 9081, fol. 26a, BN), in Hugo Buchthal, *Miniature Painting in the Latin Kingdom of Jerusalem* (Oxford, 1957); and esp. the Maciejowski Bible, no. 150, p. 116, and no. 283, p. 208 (Paris, ca. 1250, MS 638, fols. 23v, 46v, Pierpont Morgan Library, New York), in Sydney Carlyle Cockerell, *Old Testament Miniatures: A Medieval Picture Book with 283 Paintings from the Creation* (New York, 1969). I was able to view the magnificent original folios of the Maciejowski Bible thanks to William Voelkle of the Pierpont Morgan Library.

with the limits of my materials. Since there is no obvious interpretation for the main supporting structure al-Tarsûsî describes for the Frankish trebuchet, I built an approximation of one shown in the Maciejowski Bible, folios 23v and 46v (figs. 1 and 2). The Maciejowski Bible trebuchet shows all of the supporting braces hidden behind the figures around the base of the machine. The braces, therefore, do not go more than about halfway up the uprights. When I compared various ways of bracing the uprights, I found that this way not only used much less lumber than any plausible interpretation of al-Tarsûsî's drawing, but it also seemed more stable. The ground plan of my machine is similar to the well-known 13th-century drawing by Villard de Honnecourt for a counterweight machine, except, of course, that mine has less bracing and no provision for a winch.[55]

The frame of my machine was made of pressure-treated lumber and assembled with threaded rod, washers, and hexagonal nuts. Although initially cost-effective, the threaded rods turned out to be a tremendous nuisance, and the cheap wood warped and had to be squared up. Custom-cut and seasoned lumber was not an option given initial time and funding constraints.[56] If the machine were made of high-quality wood, as al-Tarsûsî says it ought to be, then it would be possible to fashion wood-to-wood (perhaps mortise-and-tenon) joints that would hold the frame together at least as well as the threaded rod. Such a frame could then be secured with the cords and iron fittings that al-Tarsûsî suggests, presumably in a way that would permit the structure to be easily dismantled, transported, and reerected. Whereas I do not think that a conjectural "replica" machine relying entirely on carpentry and lashing would take significantly longer to erect, such a machine would take a 20th-century artificer much longer to construct. Very little is known about carpentry in this period, and one must rely on what is plausible and probable.[57] I believe the construction I employed is functionally indistinguishable from a high-quality wooden structure with mortised or otherwise interlocking and lashed joints and that the

[55]See Villard de Honnecourt, *Carnet de Villard de Honnecourt: d'apes le manuscrit conservé à la Bibliothèque nationale* (Paris, 1986).

[56]The cost of the material for the machine approached $500 (Canadian) in the summer of 1989; the 1991 overhaul cost more than the machine itself did in the first place.

[57]See Sean McGrail, ed., *Woodworking Techniques before* A.D. *1500: Papers Presented to a Symposium at Greenwich in September, 1980, Together with Edited Discussion,* archaeological ser. no. 7, BAR international ser. 129 (Greenwich, 1982). Philip Walker's contribution, "The Tools Available to the Medieval Woodworker," especially makes clear just how little we actually know for certain about woodworking in the period. The problem of reviving a lost or foundering craft tradition, and especially the usefulness of modern tools in the attempt, is exceptionally well treated in Tedd Benson and James Gruber, *Building the Timber Frame House: The Revival of a Forgotten Craft* (New York, 1980).

FIG. 1.—The testing and demonstration of the full-scale reconstruction of a medieval traction trebuchet on the Back Campus of the University of Toronto, April 12, 1991; the author instructs the crew and prepares to reset the sling. Note the knots in the pulling cords tied by the crew.

FIG. 2.—In the Maciejowski Bible, folio 46v, the operator holds the sling with both hands and discusses the next shot with an assistant. The slight upward bend at the tip of the rotating beam stands in for the more sophisticated iron hook found in other machines. There is a strap below the sling because this machine is large and the beam's starting position must be high to compensate for the shallow effective hook angle. (Sydney Carlyle Cockerell, *Old Testament Miniatures* [New York, 1969], no. 283, p. 208, detail.)

necessary compromises have affected the endurance of the machine rather than its performance. For critical parts such as the axle, dense hardwood was used with a bushing of equally hard wood, just like that described by al-Tarsûsî.[58] The braces forming the characteristic triangle on the beam are attached to the beam with rope, and the beam is lashed to the axle.

[58]A good grade of maple was used instead of the recommended holm oak, which would have been *very* expensive.

Finding a suitable piece of lumber for the beam was very difficult. In the end, I laminated two straight-grained pieces of cedar. Although they are sawn, they come fairly close to that section of a tree that one would obtain by splitting it and hewing it to size. It seems more likely that the lumber for these machines was split and hewn than sawn, although some manuscripts (notably the Maciejowski Bible) clearly show the use of whole saplings.[59] Medieval wood was stronger than most commercially available modern wood because it tended to have a denser grain structure and because it was not usually sawn indiscriminately into boards before the craftsman had even decided how to use it.[60] The two-ply lamination of modern sawn wood was probably about as strong as a single piece of split and hewn medieval wood, albeit less durable. Cedar was chosen for two happily coincidental reasons: first, this is al-Tarsûsî's recommendation in lieu of cherry; and second, cedar turned out to be the *only* kind of wood available in a 16-ft. clear length.[61]

The original arm showed signs of wear and it was necessary to reinforce it for the 1991 trials and to replace it altogether for the 1992 demonstration. The wear was most pronounced just past the intersection of the two bracing arms and the main beam, the point of greatest flexure: it took the form of dents and abrasions caused by the ring of the sling striking the arm after each shot, as well as of small cracks on the bottom (compression) side caused by excessive bending stress. A tapered splint of ash was hewn from a suitable plank and lashed to the underside of the beam after most of the damaged wood had been removed with a plane. This repair not only retarded the deterioration of the arm for long enough to complete the 1991 trials, but it also seems to have increased the springiness of the beam, improving the perfor-

[59]The arrival of the counterweight machine coincides approximately with an increase in the availability of mill-sawn lumber in continental Europe, sawmills appearing in France ca. 1200, but not in England until the 18th century. See Oliver Rackham, "The Forest: Woodland and Wood-Pasture in Medieval England," in *Archaeological Approaches to Medieval Europe,* ed. Kathleen Biddick, Studies in Medieval Culture 18 (Kalamazoo, Mich., 1984), p. 80.

[60]It is worth noting that foremost among the problems to overcome when building ship replicas of the early medieval period is the acquisition of suitable building material, for the properties of the material will profoundly affect the performance of the finished product. See Crumlin-Pedersen and Vinner, eds. (n. 51 above), esp. sec. 3, "Materials and Tools." Svante Lindqvist, in his reconstruction of a late medieval treadmill, noted similar difficulties, observing that modern carpentry involves a much smaller scale than medieval work. See Svante Lindqvist, *Projekt "Det Medeltida Tramphjulet"* (*Daedalus,* Särtryck ur Tekniska Museets Årsbok, 1981). Tools and methods which might appear crude and inefficient from a modern perspective turn out to be ideally suited to the tasks for which they were originally developed; broadaxes and chisels, for example, are ideal for shaping and joining large timbers. The problem is the skill required to employ the appropriate tools.

[61]It is almost certain that al-Tarsûsî had in mind a different species of cedar, but this was as close as I could get.

mance of the machine. I cut a "closely knotted" cedar tree in the summer of 1991 in time to season it and fashion a new beam for the 1992 demonstration at Penn State.[62] Although the quantitative results reported below were recorded with the original laminated arm, the solid wooden one worked just as well.

The final *dimensions* of the machine were in part determined by the available lumber: the rotating beam is 16 ft. long, the uprights are 12 ft. high, and the struts at the base are 12 ft. and 16 ft. But I worked out the *proportions* of the machine geometrically, using only dividers and a straight-edge.

A number of the written sources that mention trebuchets also mention the iron hook that holds the sling at the end of the rotating beam.[63] For this experimental machine, I made a hook whose shape and angle could be adjusted. Although many manuscripts show curved hooks, some curved so sharply that they could not possibly work, I had the best results with a straight "hook," or "style." A curved hook turns out to be easier to use because it prevents the sling from slipping off in the moments just before shooting, but the curve must be just right in order for it to work properly; I prefer straight hooks because they are much more predictable. At first, the hooks were made with 5/8 × 3/16-inch mild-steel bar stock, which was slightly drawn out and then drilled with a 5/16-inch hole at one end. The other end was gently tapered. These hooks were simply held in place with a ¼-inch bolt and lock washers, and they were prevented from turning by spur washers.

I began with three hooks: a straight one 8 inches long, a slightly curved one 3 inches long (both of which shot quite well), and a steeply curved one 8 inches long (which shot so poorly that it was set aside as a safety hazard). In order to eliminate any chance of failure for the 1991 public demonstrations, I made a new set of straight hooks, 2½, 5, and 8 inches long.[64] These were considerably sturdier and had lock-down screws fitted so that a hook could be removed and replaced at exactly the same angle, for the angle setting was preserved in the adjusting screw.[65] (See fig. 3.) In addition, a gauge (or "jig") was made so that the

[62]This replacement arm was made entirely with traditional hand tools. I would like to thank Steven Muhlberger for the privilege of felling timber in his woodlot.

[63]Notably Abbo's account of the Siege of Paris in 885–86; see Gillmor (n. 18 above), p. 3. Unlike many other technical details, the shape of the hook can be clearly distinguished from a distance: it is the highest point on the machine when the arm is up, and its silhouette can be seen against the sky in a particularly dramatic way at dusk and dawn.

[64]Darrell Markewitz, who in 1991 was blacksmith at Black Creek Pioneer Village and is now the proprietor of the Wareham Forge, very kindly forged the blanks for these hooks to my specifications.

[65]The solution to this and several other problems of fine detail benefited greatly from discussions with technical genius Nick Blacklock.

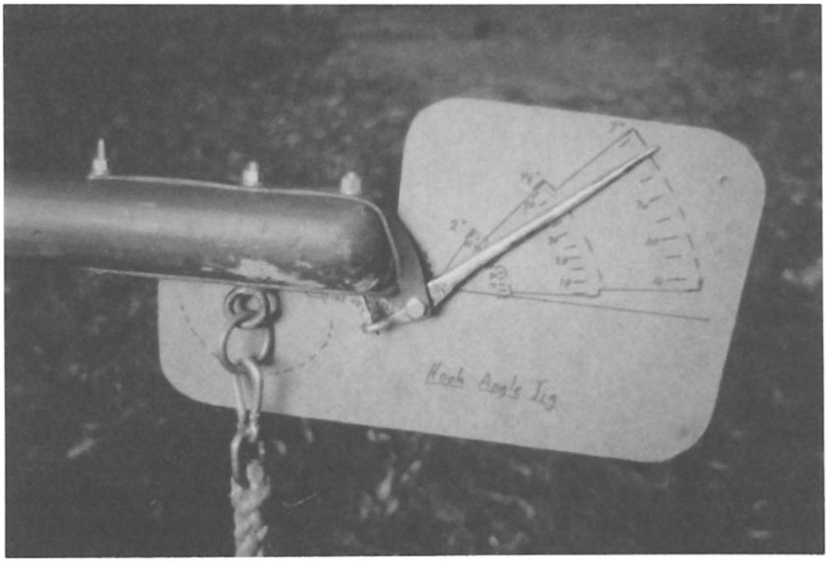

FIG. 3.—The adjustable hook at the tip of the rotating beam of the reconstructed traction trebuchet and the jig for setting or measuring its angle.

hook's angle could be set and measured relative to the arm. Based on the 1991 data,[66] I forged a one-piece hook for the 1992 demonstration; it was held in place with an integral spike pounded into the new beam and lashed fast. The overall angle of the hook needs to be around 30 or 40 degrees for the machine to work. Small variations either do not matter or can be compensated for by the operator. This is true also for the sling length, which ought to be about 40 inches for a machine of this size.[67]

The pouch itself is my best guess—it works—but I would very much like to find an authentic pattern for the cut of the pouch and the method of affixing the ropes. For the 1991 trials I devised a system of interchangeable extensions so that the length of the sling could be changed by fixed increments. The 5/8-inch manila rope was spliced so there would be no danger of knots coming undone. For the rings, I used chain links 2 inches long by $1\frac{3}{8}$ inches across and 3/8-inch thick rather than round rings so that these narrower "rings" could not foul on the

[66]The length of the hook did not seem to make much difference, but I developed a preference for the 8-inch one.

[67]That is, 80 inches extended, 40 inches doubled. The existence of a tolerance zone in hook angle and sling length within which the machine operates very close to its peak efficiency has been demonstrated experimentally by means of a small model of a counterweight trebuchet in an unpublished paper by Wilfred G. Lockett.

bolts retaining the adjustable hook. There must have been as many ways of making hooks and slings as there were siege engineers. If the projectile stays in the pouch until the ring comes free of the hook and then tumbles away cleanly, the sling works. The iron ring which fits over the hook has a more important function than to prevent wear on the rope: it acts as a small weight that keeps the sling extended after the rock leaves the pouch, preventing it from getting tangled after each shot.[68] The ring then tends to bang the arm, providing an excellent reason to wind the arm with rope. Arms wound with rope, therefore, do not necessarily indicate composite beams in the manuscript evidence.

At first, three rings were set in the butt end of the rotating beam because several illustrations clearly show this number.[69] This was increased to eight for the 1991 trials in order to distribute the load more evenly. I made the butt end of the beam heavy enough that it provides some counterbalance to the long end. This block at the butt end of the beam not only provides the necessary space to mount all the rings for the pulling ropes, but it also makes the operation of the machine much easier, provided that the long end of the beam is still slightly heavier.[70]

The finished machine has fewer than two dozen main structural components. No single part of it is too heavy for one person to lift. With all of the parts ready and several competent helpers, it can be set up or taken down in one hour. Once assembled, the machine can be carried by six or seven strong men at a walking pace. Once set down, however, it is extremely stable and rarely moved during use. It would not be difficult to make a machine of this type with no metal parts whatsoever, which cannot be said of reproductions of ancient torsion artillery.

The initial 1989 testing was carried out with fieldstones ranging in mass from 1 kg to 4 kg, but concrete balls were cast in graduated sizes for the 1991 tests. The balls were made so that their increments in volume, and therefore in mass, would be equal.[71] Although this process

[68]The operator must remain alert, however, for the ring often comes whipping around rather quickly as the beam comes back down!

[69]Most notably, the Maciejowski Bible (n. 54 above).

[70]See William of Tyre, *History of Outremer* (Acre, ca. 1280, MS 828 [715], fol. 33r, Lyons Bibliothèque Municipale), in Buchthal (n. 54 above), pl. 131a. Blocks of this sort have sometimes been confused with heavy counterweights, which they are not.

[71]This was achieved by building up five Styrofoam balls with papier- and J-cloth-mâché, including a casting sprue of cardboard tube. These "matrices" were then painted with hot paraffin wax, and their volume measured by water displacement until the volume increments between balls were equal to within less than 5 percent. (My thanks to Greg McDonald for helping with this tedious kitchen-counter procedure.) The matrices were then wrapped in automotive fiberglass, which, once cured, was cut away into two halves. To cast the balls, the insides of the molds were oiled, and a wire mesh cage was enclosed in each mold. The reinforcing mesh was added for safety reasons: if a crack were to go

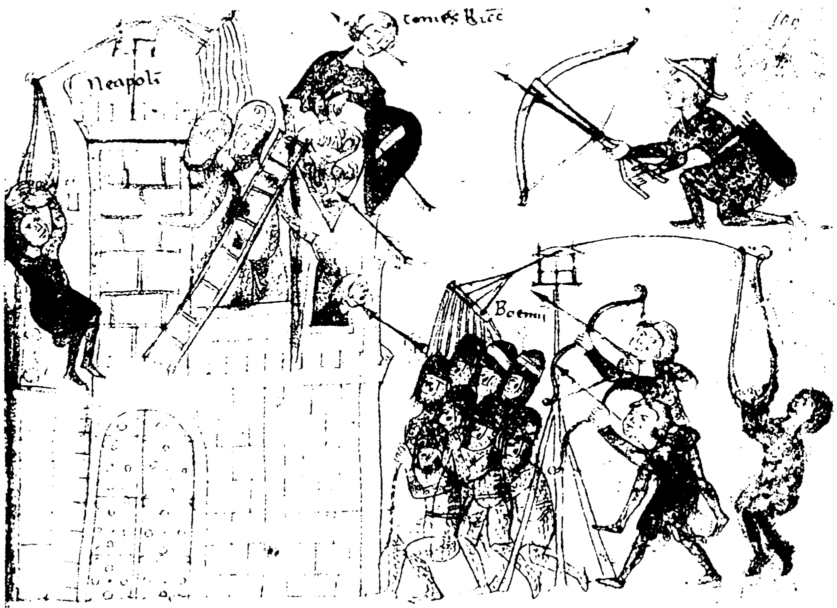

FIG. 4.—A late-12th-century Italian manuscript shows the operators of pole-framed traction trebuchets (*'arrâdah*) doing exactly as al-Tarsûsî says they ought: "The shooter should have his feet wide apart, grasp the pouch with his hands, and sit down while he pulls the pouch each time [B136r]" (n. 53). (Petrus de Ebulo, *Liber ad honorem Augusti* [1195–97]; MS 120, fol. 109r, Burgerbibliothek, Bern.)

was extremely time-consuming, adding up to several hours per ball, the balls thus produced were uniform in size and weight. Any differences in the distances that a given size of ball was thrown could only be attributed to the operation of the machine itself.

Results and Analysis of the Reconstruction

The machine worked best when the crew's placement most closely resembled the various medieval illustrations.[72] (See figs. 4 and 5.) The

undetected, the wire mesh would prevent the ball from disintegrating into fragments over the heads of the people operating the machine. The molds were sealed with duct tape and elastic bands, and filled with sand-mix concrete. After setting for a day the molds were split, the sprues knocked off, and the balls wrapped in wet rags and placed in plastic bags to cure for several days. Thus, every ball of a given size was made from the same mold, and every batch of concrete produced one ball of each size.

[72]For the disposition and appearance of the crew, see esp. William of Tyre, *History of Outremer*, "the crusaders besiege Antioch," pl. 5 (Manuscrit français, fol. v. IV. 5, fol. 18v, M. E. Saltykov-Shchedrin State Public Library, Leningrad), in Buchthal (n. 54 above); and Azarpay (n. 41 above), figs. 28 and 29, p. 65.

FIG. 5.—Holding the sling "one span" out past the end of the beam, the author grips it tightly as the crew begins to pull down on the ropes.

Maciejowski Bible clearly shows only three ropes going straight down from the butt end of the rotating beam. I originally tried to retain this characteristic while increasing the size of the crew by passing the ropes through pulleys and placing a section of the crew at the end of each of the ropes, but this proved unsatisfactory. Pulling straight down while standing directly under the butt end of the beam worked best, even though this limited the size of the crew to a maximum of twenty-five people. Moreover, if the crew crowds directly under the machine, it becomes possible to build a defensive structure around them. Al-Tarsûsî discusses this, but those sections of the manuscript were initially unavailable to me; since none of the tests of this machine were to be carried out with anyone shooting back, forgoing the defensive mantelets seemed to be a reasonable concession. While my first impression from the 1989 tests was that twenty people form an optimally sized crew for this machine, the cumulative effect of the many small improvements made for the 1991 trials was that twelve pullers proved to be just as effective. The changes that made the greatest difference were the provision of sufficiently thick pulling rope and work gloves, although the crews still tied many knots in the ropes to get a better grip. Any willing group of people can learn to pull the ropes in a surprisingly short time, but range does increase slightly with practice. By shooting as fast as possible (a bit over four shots per minute) the operator and the

FIG. 6.—In the Maciejowski Bible, folio 23v, the operator is pulled up into the air before he lets go of the sling. (Sydney Carlyle Cockerell, *Old Testament Miniatures* [New York, 1969], no. 150, p. 116, detail.)

crew fall into a rhythm which makes the shots more powerful and consistent.[73]

This is the drill that produced fast, consistent shooting at the 1989 trials: the crew pull down as hard as possible just before the shot is released, and their traction is sometimes great enough to lift the operator right off the ground (fig. 6). At the moment when the pull becomes greatest, the operator lets go of the pouch containing the projectile. The arm swings up, the rock flies from the pouch—which sometimes makes a whip-cracking sound—and the arm is easily stopped by its ropes shortly after it passes through the vertical position (fig. 7). Most of the crew give slack to their ropes except for a few whose job it is to ease the beam back down to the operator. By the time the beam comes back, the operator has regained his balance and picked up the next rock (or has received it from an assistant). He resets the sling on

[73]Some sort of a chant or shanty could prove helpful here; it is easy to imagine derisive songs about the besieged. Unfortunately, documentary evidence of this practice has thus far eluded me.

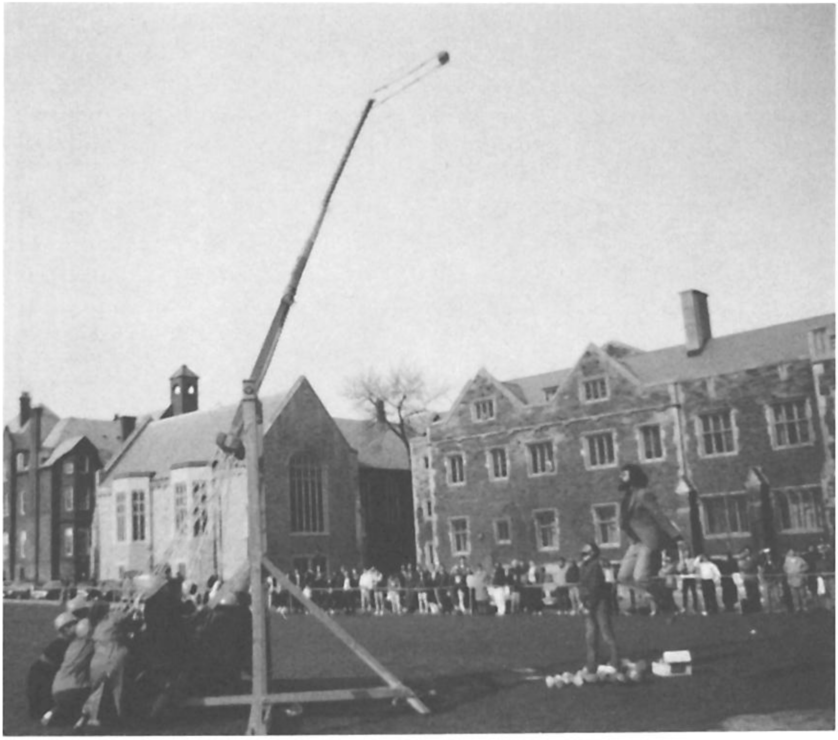

FIG. 7.—Having been pulled up into the air by the force of the shot, the author now begins to fall back to the ground while his assistant looks on. At the same instant, the sling is just starting to come free of its hook at the end of the rotating beam, releasing the projectile.

the hook while the crew readies their grip for the next shot. Six to eight seconds after the last shot, he may glance up to see where the last stone is falling.[74] A moment before the stone is quite in the pouch, the operator calls "ready!" and the slack is taken up by the crew. By the time the crew responds, the stone is securely in the pouch; the beam tugs up, and the operator locates the pouch relative to the beam in the correct position, depending on his aim. Seeing that everything is in order, the

[74]Projectiles stayed in the air for only about two-thirds as long in 1991, on average between 3.5 and 5.5 seconds. Only qualitative records were kept of the actual trajectories, but this discrepancy may indicate that a lower, more efficient trajectory was a key element of the considerable increase in performance associated with the 1991 overhaul of the machine. A lower trajectory compensates slightly better for the effects of air resistance. Much more important, however, it also means that the projectile is accelerated longer before it is released.

operator calls for "tension!" and grips the rock through the pouch with all his strength. The beam flexes and the machine creaks under the strain as the crew throw themselves at their ropes. As the tension peaks about a second later, the operator calls "release!" and lets go of the pouch. Fifteen seconds have elapsed.

In the 1989 tests, the machine was able to shoot rocks weighing around 2.5 kg an average distance of 100 m with twenty pullers. The longest shot was 137 m with a 1.9-kg stone. The shortest shots were about 40 m with twenty pullers trying to lob 8 kg and with two pullers tossing 1.6 kg. An undersized crew of eight could make shots of 60 m with stones between 2 kg and 3 kg. This already compared favorably with al-Tarsûsî's stated range limits of 80 m–120 m. After the 1991 overhaul, however, the machine threw heavier balls a greater distance more frequently with a smaller crew. Precise quantification is very difficult, but I estimate that the power of the machine was at least doubled using the same shooting procedure as outlined above.

Then an even more effective method of shooting was discovered.[75] Very simply, the crew counts to three, giving a light tug on each of "one" and "two," and hauling through on "three." This slightly slows the rate of shooting but coordinates the pull of the crew to a remarkable extent. It is less safe, however, because it is difficult to stop the "countdown" if some hazard presents itself and because the jerking of the arm on "one" and "two" can dislodge the ring from its correct position on the hook. Experimental archaeology alone cannot recover the social factors that must have influenced the choice of one shooting technique over another in the Middle Ages, but it can provide several possible solutions from which to choose on the basis of other information; the precise shooting drill probably varied widely according to local customs and conditions.

Even though the machine works with a fairly wide range of hook angles and sling lengths, consistently sized ammunition is crucial for accurate shooting because the mass of the projectile is an integral part of the dynamic system which propels it. In 1989, I could usually strike a round target 10 m in diameter a distance of 90 m away on the second shot given consistent ammunition, and accuracy improved in 1991. Medieval artillerists took great care to control the weight of their shot, having each projectile chiseled to a near-perfect sphere.[76] Chevedden reports that the sites of some medieval sieges, especially in the Middle

[75]Credit for this discovery is due to Frank Klaasen.

[76]Contamine (n. 24 above), p. 104, writes that "in 1244 round trébuchet stones were being produced in large quantities through the efforts of the English government." (These may have been meant for counterweight trebuchets, however.)

East, are still littered with stones which resemble rough-hewn bowling balls in various sizes.[77] When shooting, the lateral drift seldom exceeded 3 m to either side of the line of shot, so the spotters were comfortable standing 15 m away from the target area.[78] The range can be adjusted to some extent by pushing the missile slightly off to one side for lateral aiming or by holding it backward or forward to correct for distance. By far the easiest way to aim is to optimize the performance of the machine, throw a few test stones, and then move the whole machine so that the drop zone is over the target. Naturally, identical ammunition is best, but a competent operator should be able to compensate for variations of up to plus or minus 10 percent in mass.[79]

The following are some examples of the cluster patterns attained by the machine in Toronto in 1991. A crew of sixteen pullers with a 41-inch sling and a 5-inch hook set at 40 degrees discharged six 4.7-kg balls in one minute and ten seconds to distances of 81, 79, 76, 77, 76, and 76 m. The same crew took the same length of time to shoot six 3.9-kg balls moments later, achieving distances of 77, 89, 94, 89, 94, and 89 m. Using the "one, two, three!" count, a different crew of fifteen pullers using the same hook and sling settings shot six 4.7-kg balls to distances of 100, 90, 105, 100, 105, and 93 m. The second 100-m ball landed on the first, destroying both. A skeleton crew of four with a 41-inch sling and an 8-inch hook set at 40 degrees tossed six 3.1-kg balls to 65, 68, 52, 69, 55, and 69 m in one minute and fifteen seconds. When there was a bit more time to practice at the end of the day, a crew of fourteen used the same settings and a 3.1-kg ball to achieve the maximum recorded range of 145 m.[80] There are medieval reports that women operated this kind of siege engine in times of crisis, most notably the legend that Simon de Montfort met his demise in this way at the siege of Toulouse in 1218.[81] A female crew was tried and compared to the male crew. The women's drop zone was closer than, but overlapped with, the men's; the small

[77]Chevedden brought one such projectile to the 1991 Toronto demonstration. Originally from the citadel of Damascus in Syria, with a mass of 5 kg, it was hurled 83 m by a twelve-person crew.

[78]This permitted close observation of the incoming missiles: one observer noted that the falling balls sometimes made a high-pitched hissing sound as they approached and that he could see them spin as they dropped; other observers could feel the earth shudder beneath them when the balls struck the ground.

[79]Of course, one can imagine situations where precise accuracy was not a great concern, or where uniform ammunition was simply unavailable.

[80]The intermediate shots are not recorded, but the shots were deliberately "walked" out to within 15 m of the fence bounding the field, the crew counting "eins, zwei, drei!" in German, a language they found suitably martial. We recorded the last shot and decided not to press our luck any further.

[81]Viollet-le-Duc, *Dictionnaire* (n. 9 above), p. 233.

difference in performance could be easily explained by the lower average weight of the women. Pound for pound, therefore, a female crew shoots as well as a male crew for all practical purposes. An Italian manuscript from 1195–97, Petrus de Ebulo's *Liber ad honorem Augusti,*[82] clearly shows archers and a crossbowman operating within the range of the traction trebuchet. The maximum effective range of archers and crossbowmen before the Welsh longbow and the steel crossbow was between 100 m and 150 m, approximately the same as the traction trebuchet.

The Petrus de Ebulo illustration also shows the beam flexing in the moment prior to the release of the pouch by the operator. Unlike the counterweight trebuchet, which lobs the stone in a single, continuous sweep, the traction trebuchet discharges its missile with a sharp snap. Frame-by-frame examination of the videotape of the 1991 test[83] showed that the arm went through four distinct phases on each shot, each representing an approximately equal segment of the beam's total rotation, which is a little over 90 degrees. Al-Tarsûsî instructs the operator to hold the stone in the sling out past the end of the beam by a distance of 1 span. In the first phase, right after the operator lets go of the pouch from this position, the stone falls in *toward* the flexed beam as the crew pulls down on the short end and the long end begins to straighten and move upward. In the second phase, the crew continues to apply power and the arm continues to accelerate upward, but the sling changes direction and begins to swing back out. By the third phase, the crew is no longer at an angle with respect to the beam where they can apply much more useful power and the beam just "coasts." The sling, however, now whips around at great speed and flexes the beam back again, in some cases pulling the tip of the beam back enough to momentarily arrest its forward motion altogether. The crew can feel this quite distinctly as the moment of maximum resistance on the follow-through of each pull. The sling releases the projectile just before the arm is decelerated and stopped by the pulling ropes, which are now vertically in line with it; as the beam decelerates in the fourth phase, it flexes forward (i.e., in the direction opposite to its previous flexure), and the sling falls forward in an arc, kept extended by the weight of the iron ring at its extremity. This motion is fairly subtle, and when it is observed from the side, it looks as if the sling remains more or less perpendicular to the beam until just before the moment of release, whereupon it swings out and forward with great force. In fact, it looks eerily Aristotelian, as if there were a sudden transition from circular to

[82]MS 120, fol. 109r, Burgerbibliothek, Bern.

[83]I thank Chris Darroch for videotaping the 1991 Toronto trials.

linear motion. This effect can be used to aim the stone, for an experienced operator will have a keen feel for how the machine will amplify the nudges he gives the stone at the moment of release.

This action of the sling and beam explains why the flexibility of the beam is stressed by al-Tarsûsî as an important parameter. By flexing, the beam stores energy in the brief interval between the application of full tension by the crew and the release of the pouch by the operator. The beam then returns this stored energy as it straightens. The next time the beam flexes, in the third phase, it buffers the snap of the sling, allowing the crew members to follow through on their pull without unduly wrenching their arms. But why does folio 23v of the Maciejowski Bible not show the beam flexing, even though it shows the operator being pulled into the air before he releases the sling? I suspect that the flex is more important in smaller and Arabic machines, whereas the heavier and more rigid braced beams of larger and "Frankish" engines achieve much of their third-phase buffering by means of their considerable angular momentum.[84] The effective hook angle of the natural bend at the tip of the rotating beam of the large Maciejowski Bible machine was so shallow that the sling would release early and the trajectory would be too high if the rock were held low enough for the operator to grasp the pouch directly, which explains the need for the cord below the sling. (In fact, fol. 46v shows the operator holding the pouch down low, and there is a figure standing beside him pointing up, where the rock would go if it were shot from this position.)

Thus, the sling actions of the traction and the counterweight trebuchets are quite different, each making the most efficient use of its respective energy source. The long sling characteristic of the counterweight machine is not suitable for a traction trebuchet because the snap is impossible with a long sling, given the relatively short distance in which a crew can exert its pull. Also, a long sling tends to get tangled, and one advantage of the traction machine is its fast rate of shooting. Conversely, the short sling of a traction trebuchet would tend to release too early in a counterweight machine, sending the missile either backward or straight up. The swing of the arm being much longer, the heavier projectile can and must accelerate more gradually; the long sling allows it to do this.

[84]A corollary of this hypothesis is that the two main forms of the traction trebuchet (i.e., the pole-framed *'arrâdah* and the trestle-framed *manjanîq*) may correspond to two distinct performance optimization strategies, but further research and experimentation would be required to bear this out. Werner Soedel of Purdue University explained the pivotal role of angular momentum in counterweight machines in "The Kinematics of the Counterweight Trebuchet" (paper read at the Twenty-eighth Medieval Congress in Kalamazoo, 1993).

Conclusions

The findings of this project support several conclusions. First, the traction trebuchet was a serious engine of war in its own right, and not merely a diminutive version of the counterweight trebuchet. This machine provided a viable alternative to the onager soon after the collapse of the Roman Empire and long before the introduction of the counterweight trebuchet in the 12th century. Moreover, the advantages of the onager appear minimal: more expensive, troublesome, and dangerous to build, use, and maintain, its advantage of greater range appears negligible in a world before the Welsh longbow and the steel crossbow. References in this period to *mangonels* and other miscellaneous *machinea* are far more likely to refer to traction trebuchets than to Roman survivals. It was the traction trebuchet, and not some mythical Roman onager known as a *mangonel,* that was partially superseded by the counterweight trebuchet in the 12th century.

Second, this project has vindicated the technical credibility of many of the sources used for the reconstruction. Most conspicuously, I found al-Tarsûsî's manual, the *Instruction of the Masters,* to be a field-worthy book containing advice of real practical value. Likewise, I found that the illustrations of traction trebuchets in the Maciejowski Bible contain subtle and significant technical detail. Third, it is increasingly clear that medieval Europe did not exist in a vacuum, but took ideas and influences from the whole known world. The traction trebuchet can be added to the long list of well-known technologies (including gunpowder and printing) that started in the East, diffused to the West, and flourished. As such, it represents an important episode in the evolution of technology. This now-familiar opinion was recorded at the end of the traction trebuchet's heyday: "At the beginning of the XIIIth century Guiot de Provins lamented that the artists (the knights) had to make way for the technicians, that is, the crossbowmen, the sappers, the operators of rock-throwers, and engineers."[85]

Appendix

Glossary

This glossary is not intended to be comprehensive, but to convey the wide range of meanings in general use for key terms. For a precise review of Greek and Roman terminology, see E. W. Marsden, *Greek and Roman Artillery: Historical Development* (Oxford, 1969).

[85]J.-F. Finó, *Forteresses de la France* (Paris, 1970), p. 163: "*Au début du XIII^{e} siècle, Guiot de Provins regrette que les artistes (les chevaliers) doivent céder le pas aux techniciens, c'est-à-dire, aux arbalétiers, mineurs, servants de perrières et ingenieurs.*"

Arcuballista, Arcuballistra: Either a late-Roman two-armed torsion engine or a mounted crossbow.

'Arrâdah: The Arabic name for a pole-frame traction trebuchet which can be swiveled and therefore easily aimed laterally.

Ballista: Before the 2d century A.D., a two-armed torsion-powered rock thrower. After the 3d century A.D., a two-armed torsion-powered arrow projector.

Catapult: Before the 2d century A.D., a two-armed torsion-powered arrow thrower. After the 2d or 3d century A.D., a two-armed torsion-powered rock projector. Also, a generic name for any siege engine of any period.

Machina: Generic Latin word for siege engines and other machines.

Mangonel: An ambiguous word used to describe almost any kind of late- or post-Roman siege engine; possibly either an onager or a traction trebuchet.

Manjanîq: The Arabic name for a trestle-framed traction trebuchet.

Onager: A late-Roman siege engine using a single large horizontal torsion skein with a single arm and a sling (called the "Wild Ass" because it kicks up with a considerable recoil when discharged, and because the wild ass was said to kick up stones after its pursuers).

Perrière, Petraria, Petrobolos: Words meaning "rock thrower," often but not exclusively used to describe traction trebuchets.

Rotating Beam: The largest moving part of a counterweight or traction trebuchet. The beam swings through a vertical plane about a fulcrum placed closer to one end. There is either a counterweight or a human crew attached to the short end, depending on the kind of trebuchet, and a sling and a hook attached at the long end.

Scorpion: A catchall name for several kinds of Roman siege engines, particularly but not exclusively the smaller ones.

Siege Engine, Siege Machine: An ancient or medieval contrivance for throwing substantial missiles at an enemy during sieges and related tactical situations.

Skein: The spring in torsion artillery, consisting of a very tightly stretched bundle of animal sinews or hair which stores energy when it is twisted (i.e., deflected in torsion) by means of a lever passing through the center of, and perpendicular to, the bundle; the lever is the arm of the machine. Two-armed machines require two skeins, one for each arm.

Springnal, Espringnal: Most probably a large mounted crossbow; also, a fictional machine with a bent plank which springs forward to strike a large arrow, propelling it forward.

Tormentum: Generic Latin word for various kinds of engines, including siege engines.

Torsion Engine: A siege engine used by the ancient Greeks and Romans using one or two skeins of twisted animal sinew or hair to store energy. A one-armed torsion engine (i.e., an onager) would

almost invariably have a sling rather than the highly inefficient—but unfortunately stereotypical—spoon; a two-armed torsion engine would have a bowstring (in the manner of a crossbow).

Traction Trebuchet: A small- or medium-size rotating-beam siege engine, invented in China in the 5th century B.C., powered by a human crew pulling on ropes attached to the short end of the beam. This is the only kind of siege engine which does *not* have to be "wound up" in some way to store energy before each shot.

Trebuchet (Counterweight Trebuchet): A large rotating-beam siege engine, invented in the 12th century A.D., powered by a heavy counterweight appended to the short end of its beam.