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Stone Sawing Machines of Roman and Early Byzantine Times in the Anatolian Mediterranean

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Introduction

When, in times of the *Pax Romana,* wealth increased throughout the empire, about every town gained its aqueducts supplying public and private *thermae* that became standard elements of city life. The walls and floors of these bath houses and of many other buildings were adorned with marble slabs, numerous examples to be found in the Antalya region. These marble slabs must have been produced in ever greater quantities. Manual sawing of stone is known for long going back to the 13th c. BC. Recent findings in the Anatolian Mediterranean now show that water-powered stone saw mills were known at least from Roman times. A relief on the cover of a 3rd c. AD sarcophagus at the north necropolis at Hierapolis in Phrygia (Pamukkale) shows a technical design - an extraordinary state of affairs on its own - of a water-powered twin stone saw mill. The mill is equipped with the crank and connecting rod system, previously thought to have been a medieval invention, by which the rotary movement of the water wheel is transformed into a reciprocal linear movement enabling mass production of marble slabs. Remains of a stone saw mill at Ephesos, with multiple saw blades, and at Gerasa (Jordan), both dating from the 6th-7th c. AD, show that the mill machinery improved since the Hierapolis mill had been designed. The way how the saw blades were mounted and guided to cut stone blocks into slabs remains subject to discussions among scientists.

Stone sawing

The sawing of stones, into blocs or into veneer slabs, has a long tradition going back to the 13th c. BC as is attested by traces on blocs at the acropolis of Tiryns[1]. Pliny, devoting his 36th book of NH to the history of stones, tells us that he is not sure that 'the art of cutting marble into slabs´was an invention of the people of Caria', but he mentions the palace at Halicarnassus, of Mausolus (who died 352 BC), as the oldest example of covering walls with marble slabs that he knows of[2]. In Rome, the covering of walls with marble slabs was introduced in the 1st c. BC by Mamurra, prefect of the engineers under Gaius Caesar in

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1 Bruno 2002, 188.

2 Plinius NH XXXVI, 6. Bruno 2002, 188.

Gallia, who met widespread disapproval for such base considered habit, although others soon followed, Pliny NH XXXVI,8 tells us.

The instrument that was used from early times on was the manually operated saw, exemplified by a Flavian relief from Ostia showing marmorari in their workshop proudly presenting a span saw, basic tool of their profession (Fig. 1). The saw itself consisted of a wooden beam (the cross beam), carrying supports at its ends perpendicular to the beam axis (the side arms). Between the supports, on one side of the cross beam, the saw blade was fixed, held in tension by a rope or metal wire (the tensioner) tightened on the other side, no different than for a wood cutting span-saw. The length of the saw and the distance between the saw blade and the beam determined the size of the slabs and blocs that could be sawn. Vitruvius writes that tuff stone could be sawn with toothed saws just as wood, and Pliny notes that in the province of the Belgae a white stone admits of being cut with the saw that is used for wood, with greater facility even[3]. For hard and durable material the blade was toothless, the cutting of the stone achieved by sand, 'the saw acting by only pressing on the sand within a very fine cleft in the stone, as it is moved to and fro' (NH XXXVI,9). In the Ostia relief one notes in front of the stone bloc an amphora, cut in half, container for the mixture of sand and water, and a long rod ending in a spoon, to deposit the mixture into the saw-slot, which means that the saw was operated by a single labourer[4]. In the towns stone sawing activities often took place near the harbour, which were at risk of being silted because of the sands needed for the sawing and the marble powder produced by the sawing process. An edict found at Ephesos, of L. Antonius Albus, proconsul of Asia (146-7 AD), banned the marmorari for that reason from the quays[5]. Findings in the late 1800's revealed the huge amount of over 40.000 fragments of ancient veneers in the deposits of the Marmorata at Rome, confirming the exensive use of marble veneer[6]. The sawing of stones was not restricted to the marble studios. In quarries enormous blocs were cut right out of the stone. At Chassambali, near Larissa, Greece, long slits from sawing activities may be seen, while also a 124 cm long fragment of a 3 mm wide saw blade was found; Felsberg (Germany) is known for its 'Altarstein' sawn out of grey granite; at Dokimeion (Phrygia), a saw of an astounding 8 m length must have been operated by at least 2 labourers[7].

Sawing machines

Millions of square meters of slabs must have been produced from the 1st c. AD onwards when marble cladding of buildings became increasingly fashionable[8]. All such material was not produced by manual sawing alone. Four straightforward examples exist of sawing machines in antiquity, all driven by water power. The remains of two sawing mills in marble work shops, at Ephesos and Gerasa (Jordan), from which technical details may be derived, both date from 6th-7th c. AD. Third example is Ausonius' poem Mosella,

3 *Quod etiam serra dentata uti lignum secatur,* Vitruvius 2.7.1; Plinius *NH* XXXVI, 44.

4 Olivanti 2002 (with illustration of the relief).

5 Wankel 1979, nr. 23, 13-16. Also Bruno 2002, 190.

6 Maischberger 1997, 71-74. Bruno 2002, 190 mentions 'circa 60.000 lastre'.

7 These and more examples see Bruno 2002, 188-9.

8 Mangartz 2010, summary.

ca. 370 AD, in which the sounds of marble saws driven by the waters of the river Erubris (Ruwer) are mentioned, no technical details referred to. Earliest proof for the existence of sawing machines Roman times comes from a funerary relief at Hierapolis (Phrygia), dating from the 3rd c. AD.

Hierapolis

In 2005 a relief on the cover of a sarcophagus at the north necropolis at Hierapolis in Phrygia, Turkey, could be identified as a water-powered stone saw mill (Fig. 2a, b)[9]. The inscription on the cover mentions M. Aur. Ammianos as the owner of the sarcophagus; it could be dated to 2nd half of the 3rd c. AD. Ammianos is described as τροχοδαιδαλος, i.e. an inventive and able man, working with wheels[10]. The relief shows a large vertical water wheel with a long shaft extending to one side. The shaft is equipped with a secondary gear train of two smaller, vertical gears. From the third wheel two slanted rods extend, one to the left and one to the right, towards what evidently are vertical saw frames. The saw blades have progressed halfway through rectangular stone blocs. As the saws evidently should move to and fro, rotation must be transformed into a reciprocal linear movement at the third wheel, from which the slanted rods extend towards the frames. This of course can only be achieved by means of the crank and connecting rod system, a crank fixed to the rotating shaft of the third wheel, with a rod attached to it, pushing and pulling the saw frames. In Fig. 3 a reconstruction of the Hierapolis mill is proposed. On either end of the shaft of the third wheel a crank or crank disc is fixed (both options are shown). A simple wooden guiding frame is depicted for the left saw.

Ausonius

The sound of grain mills and marble saws driven by the waters of the river Erubris (Ruwer) is described Ausonius' poem Mosella, written about 370 AD: 'Turning the stones in headlong rotation and drawing the creaking saws through shining marble, it (the Erubris) hears an incessant noise on both its banks'. The poem has long been considered proof for the existence of sawing machines in Roman times[11], but in the 1960's the notion that the crank and connecting rod system could not have existed in Roman times had led to the idea that the Mosella poem in reality was a 10th c. addition to his works[12]. Only in the early 1980's this opinion was proven false and the poem accepted as genuine[13]. Yet, it could still not be imagined that the Romans knew the crank and connecting rod, for which indeed proof was lacking, and to meet with the Ausonius poem scholars proposed alternative mechanisms as circular saws and continuous wire saws which these all meet severe technical problems[14]. Since the interpretation of the Hierapolis relief it is now accepted that the Romans knew the crank and connecting rod system, and applied the

9 Ritti *et al.* 2007.

10 The inscription reads 'M. Aur. Ammianos, citizen of Hierapolis, skillful as Daedalus in wheel-working, made (the represented machine) with Daedalean craft; and now I will stay here'.

11 Neuburger 1919, 402.

12 White 1962, 82-3; Reynolds 1983, 31; Lewis 1997, 114.

13 E.g. Wikander 2000, 404. Seigne 2006, 383.

14 Humphrey et al. 1998, 34; Simms 1983; for a discussion see Seigne 2006, 383. Also Lewis 1997, 114. But see also Mangartz 2006, n. 32.

system for industrial uses, for their stone sawing machinery at least, and that Ausonius had it right with the sound of machines sawing marble north of the Alps.

Gerasa

In 2000 Jacques Seigne of the Univerity of Tours, France, discovered the remains of a Byzantine multi-bladed water driven twin stone saw in a room of the cryptoporticus of the temple of Artemis at Gerasa, Jordan (Fig. 4)[15]. From a reservoir above this room water was led down to a 4m vertical water wheel. Two lime stone drums, spolia from the temple measuring 1.51 and 1.67 m long and 1 m diameter, were found in the room, each with sets of 4 parallel saw-cuttings that all have progressed to the same depth although the outer surface is curved (Fig. 5). The in situ walls of the wheel race show rectangular cuttings to allow for the bearings of the shaft of a water wheel. Both outer faces of these walls have circular wear marks caused by friction of some revolving object. From this is was concluded that there had been two crank discs, of at least 1 m diameter, fixed to the shaft of the wheel on either side, each crank disc equipped with an eccentric pin from which a connecting rod ran to a vertical saw frame. The saw frames each carried 4 parallel saw blades. Straightforward wooden guiding frames are thought to guarantee vertical progression of the saws (Fig. 6). According to Seigne, the vertical saw frames did not require compensating counterweights. He also excluded horizontal saw frames because of the disproportionate dimensions that would have been necessary. A 1 to 1 reconstruction on the original location was realized in 2007 (Fig. 13)[16]. As the Gerasa stone saw mill was constructed later than 5th c CE when the temple of Artemis was abandoned, but before the great earthquake of 749 CE that completely destroyed Gerasa, Seigne estimates that the construction of the mill probably took place at the time of Justinian (527-565 CE), a period of extensive building activity.

Ephesos

The well preserved remains of the Byzantine water driven twin stone saw mill in Hanghaus 2 at Ephesos were discovered in the eighties of last century and were quickly recognized as a hydraulic mill for the sawing of stones. In 2006 Fritz Mangartz, of the Römisch-Germanisches Zentralmuseum, Germany, first published a reconstruction of the based on extensive research on site[17]. The Ephesos mill is located in a room on the lowest level of Hanghaus 2, at the end of at least 5 water mills built in a row on the slope of the Bülbül Dağ. In the room two rectangular marble blocs, in situ, 2.2 m long, 0.6m wide, and 1.2 m high are positioned parallel to each other, to the left and the right of a water channel in the floor (Fig. 7a). The stone blocs have been sawn for a short distance after complete slabs had already been taken off. There are two cuttings about 3 mm wide and 16/20 cm deep for each bloc (Fig. 7b)[18].

15 Seigne 2002, 212; Seigne 2006, 388;

16 Seigne 2009. The machine was demonstrated at the 13th Int. Conf. Cura Aquarum, Jordan March 31- April 9, 2007.

17 Mangartz 2006.

18 Mangartz 2006, 582.

Presumably all made of wood nothing has remained of the water wheel, the support for the bearings, the saw frames, or of the mechanisms to move the saws. Mangartz proposes a reconstruction of the mill with a 2.8 m waterwheel and a crank and connecting rod system to drive two horizontal saw frames, each frame carrying a set of two parallel saw blades (Fig. 8). The saw frames are thought hanging down at the corners from 4 ropes with counterweights over pullies, which is suggested by the finding of a stone weight with remains of an iron ring (Fig. 9)[19]. From coins found in the studio the saw mill is dated to late 6^{th} or early 7^{th} c. AD. On the State Agora a 2.35 m long and 65 cm diameter red granit column with two parallel saw slits along its length, adds to proof of sawing activities at Ephesos (Fig. 10)[20].

The mills at Gerasa and Ephesos and the Hierapolis relief

As the Ausonius poem does not provide any details on the machinery it is of limited use in the discussion on technicalities. The saw mills of Gerasa and of Ephesos on their turn show remarkable similarities. Each mill is located in a workshop, one wall equipped with the head race some 3-4 m above floor level, mill race and tail race in the floor of the shop. Two stone blocs, next to each other on either side of the tail race, were sawn into veneer slabs simultaneously. Both water wheels had a short shaft just long enough to accommodate the wheel itself and the two bearings adjacent to the wheel. Crank disks with eccentric pin were fixed onto the shaft on the outside of the bearings on either side of the wheel. There were no gears. Both mills date from the same period.

In the Hierapolis configuration the saw frames and the stone blocs are positioned to one side of the water wheel, driven by a secondary gear train fixed to the long shaft of the water wheel.

Without considering whether the saw frames were either horizontal or vertical and whether counterweights were used or not, and whether the saws were guided to ensure straight cuts, two types of saw mills must be considered. One type with a long shaft having a secondary gear train (Hierapolis), and the other with a short wheel shaft, without a gear train (Ephesos/Gerasa). All mills are equipped with a crank-and-connection rod system to transfer the wheel's rotation into a reciprocal linear movement.

For its extended shaft and secondary gear train the earlier Hierapolis mill resembles the Vitruvian water mill for grinding grain[21], be it that the right angle gears of the Vitruvian mill are parallel gears for the Hierapolis mill. For the Vitruvian mill the 2^{nd} wheel of the gear train drives the upper millstone, for the Hierapolis mill it drives the saw frames. Maybe M. Aur. Ammianos got the idea to redesing a Vitruvian water mill experimenting with an existing grain mill, as the only thing he had to do was to change the combination of vertical and horizontal gearing wheels into parallel gears, and add cranks and connecting rods, to drive a set of manual saws for stone sawing readily at hand. This would explain the long shaft and the secondary gear train of the Hierapolis stone saw mill. By

19 Earlier reconstruction exist for the Efesos mill, e.g. Schiøler 2005, also proposing a horizontal saw frame, as does Warnecke 1997.

20 W. Aylward, University of Wisconsin, is acknowledged for drawing the author's attention to the column in 2006. The saw slits show a convexity of about 5 cm to both sides.

21 See e.g. Peters 1997, 285.

the gears that Ammianos applied for driving his saws energy is inevitably lost by friction. Then, at a later stage, the parallel gears were left out and the crank disks were fitted directly onto the shaft of the water wheel itself. By taking out the secondary gear train, which had a gearing ratio of about 1,[22] friction was reduced, resulting to higher efficiency, to a wheel shaft of reduced length, and thus to less complex and cheaper machinery. This resulted to the mills of Ephesos and Gerasa (Fig. 11).

With the Hierapolis relief doubts whether the Romans knew the crank and connecting rod system have been eliminated. Water driven stone saw mills have existed at least from 3rd c. AD onwards, and maybe even earlier. All recent reconstructions of ancient water driven saw mills envisage the crank and connecting rod on behalf of the power transfer to the saws. However, while the saw blades invariably are thought to have been toothless, no *communis opinio* exists about the shape of the saw frames, about the way in which the saws were mounted and if and how the saws were guided during the sawing proecess.

Saw frames

In 2009 Fritz Mangartz conducted experiments on a 1 to 1 reconstruction of the Ephesos mill at Vulkan Park at Mayen, Germany[23]. Water wheel replaced by an electric drive, a horizontal wooden frame carrying two toothless parallel saw blades was suspended from 4 ropes at the edges with counterweights over pullies (Fig. 12). By means of a 10 cm crank and 4.3 m connecting rod the saw frame was moved to and fro for about 20 cm, to cut a block of 'Jura marmor' similarly sized as the Ephesos marble blocks. A mixture of sand and water was applied continuously by hand onto the saw slit while the sawing process was monitored. The experimental sawing proceeded succesfully to a 10 cm deep cut with a progress of 6.75 mm/hr, i.e. almost 19,000 mm^2/hr. Mangartz estimates that with 12 hour operation per day and no malfunctioning of the machine one labourer would produce about 330 square meters of slabs in a year. Sawing the stone block by hand required two labourers progressing 6000 mm^2/hr for a single slab the experiment showed. From this Mangartz concluded that in the best case the machine would produce twelve fold compared to manual sawing[24]. Although the saw frames were suspended from ropes over pullies, it turned out that this did not allow for the automatic lowering of the frames of the reconstructed saw. Mangartz did not propose any kind of guiding system to ensure straight cuts.

The Mangartz machine contrasts the Gerasa reconstruction not only because Seigne proposes vertical saw frames, but also because Seigne envisages that the saws did not require compensating counterweights. Seigne assumes that simple wooden guiding frames, allowing the saws move freely to and fro horizontally, made the saws progress down in a straight line producing slabs with a flat surface (Fig. 13). Recently Seigne revised the guiding frames for reasons of instability due to the great mass of the saw frames. Seigne did

22 Obviously the rotational frequency of the water wheel matched the required speed of the saws, so gearing up, or down, was not necessary.

23 Mangartz 2010.

24 Ibid. For less durable marbles production in mm2/hr would be higher while the production ratio machine vs manual labour remains unchanged.

not as yet test his machine cutting marble but experiments with a water driven wheel are planned in the near future[25].

The Hierapolis relief leaves little doubt that Ammianos applied vertical saw frames. The relief does not show whether Ammianos used any kind of guiding mechanism to lower his saws, nor whether compensating counterweights were applied or not; if so, the relief obviously did not allow for such details, or the issue was not important enough. The preliminary reconstruction by Kessener of 2007 proposes vertical guiding frames as for the Gerasa saws, leaving counterweights an open issue.

In a 2009 publication Klaus Grewe, of the Landschaftsverband Rheinland/Rheinisches Amt für Bodendenkmalpflege, Bonn, Germany, stresses the importance of guiding frames in both horizontal and vertical direction[26]. Grewe rejects the above reconstructions with the argument that the machines simply would not function properly, because he argues that, without both a horizontal and a vertical guiding mechanism for the saw blades, on the one hand the saw would tend to jam because of sideways tilting of the saw blade ('Verkantung') or due to horizontal rotation of the saw frame ('Verdrehung'), while on the other hand the saw slits would show convexity because of the crank-connecting rod mechanism. The circular movement of the crank causes the connection rod not to be in line with the saw frame but pushes and pulls the saw up or down a little, at an angle which differs for the to and fro stroke. From this the saw frame tends to deviate from horizontal to some extend ('Verkippung'), giving rise to a convexity of the saw slit (Fig. 14). As the saw slits in the blocks at Ephesos show only a minor convex deviation from a straight cut (15 and 22 mm)[27] Grewe argues that both a vertical as well as a horizontal guiding mechanisms are obligatory. He refers to an 18th c. German engineer named Sturm, who invented a sawing machine that did just that. Sturm designed a saw frame with pins extending horizontally from the frame. The pins, and thus the saw frame, could move up and down in vertical slots of a second frame envelopping the first. This second frame was equipped with wheels or rollers to move horizontally over some kind of railing system fixed on a platform or table. This carriage is pushed and pulled by a connecting rod from a crank driven by a water wheel. On the table between the rails the stone to be sawn is positioned, while the saw is forced down during the sawing process by adding extra weights onto the saw frame (Fig. 15).

There is little doubt that straight cuts will be produced with such guiding system. A reconstructed 18th c. stone saw mill at Schwerin, Germany, represents a working model of this system that functions today, which Grewe imagines would be similar to the Hierapolis machine. Specimens of stone blocks sawn by this machine show straight horizontal slits for their greater part, with slanted sections at the ends, which according to Grewe are caused by a shocklike motion of the saw blades due to tolerance of the vertical slots and pins when their moving direction is reversed each half cycle.

25 Seigne, pers. comm. 2010.

26 Grewe 2009.

27 Grewe 2009, 445.

So we have various reconstructions of the saw frames for ancient water driven stone saw mills. Vertical frames for Gerasa (Seigne) and Hierapolis (Kessener), horizontal frames for Ephesos (Mangartz), and a carriage system for Hierapolis (Grewe). Also on counter-weights and guiding frames opinions are contrasting: Hierapolis/Kessener, vertical guiding frames; Gerasa/Seigne, vertical guiding frames, no counterweights[28]; Ephesos/Mangartz, no guiding frames, counterweights; Hierapolis/Grewe, horizontal and vertical guiding mechanism, additional weights (Tab. 1).

Manual sawing

No doubt the inventor of the water driven stone saw mill, whether it was Ammianos or some one else, was familiar with manual sawing. Already in use for centuries in Ammianos' time, the manual saw was one of the marble worker's basic tools, which has remained unchanged unto modern times[29].

It must have been a great relief to the stone labourer when the water powered sawing machine took away the drudgery of the perpetual pushing and pulling of the saws, similar to when the water powered grain mill took away the toil of manual milling, reflected in a poem of Antipater of Thessalonica (1st c. BC):

Hold back your hands from the mill, you grinding girls; even if the cockcrow heralds the dawn, sleep on. For Demeter has imposed the labours of your hands on the nymphs who, leaping down upon the topmost part of the wheel, rotate its axle; and with encircling cogs it turns the hollow weight of the Nisyrian millstones. If we learn to feast toil-free on the fruits of the earth, we taste again the golden age[30].

The important thing was that the water wheel relieved the marble worker from the fysical effort of pushing and pulling the saws with his hands. Therefore it is of interest to understand how the manual sawing process was conducted and in what way large cuttings were made. Earliest proof of stone sawing goes back to the 13th c. BC, attested by traces on blocks at the acropolis of Tiryns[31]. The circular saw traces indicate a pendular system with a weighted saw blade hanging down from a horizontal beam made to swing to and fro, as for instance proposed by Schwandner[32]. Curved saw traces have also been found at the Hittite capital of Hattusha (Boğazkale, Turkey) and at Selinus (Selinunte, Sicily)[33]. The long slits found Roman quarries indicate that the enormous blocks were sawn right of the rock with huge saws that must have been suspended from supports with counter weights over pullies to enable manual operation (Fig. 16).

Cutting blocks by manual labour remained common practice over the centuries, exemplified by a drawing of Benoist (1869) showing the sawing of spolia at the ´Marmorata´ at the right bank of the Tiber on the slopes of the Aventine hills (Fig. 17). Although Benoist clearly did not intend to make a technical drawing some conclusions may be drawn from

28 Recently Seigne added counterweights to his machine compensating for the weight of the connecting rods (Seigne 2009, 439).

29 Bruno 2002, 188.

30 Cited from Lewis 1997, 66.

31 Bruno 2002, ibid.

32 Schwandner 1991, fig.6, Fig.8.

33 Bingöl 2004, 119-20 figs. 212, 213.

it. On the foreground a tall marble block is sawn by a single man operating a pendular saw, apparently without great effort. The saw, and the block, are as high as the man himself. The labourer being, say, 1.75 m tall, the saw blade would be about 2 m long. In the background an even larger block is sawn by two labourers, with a saw at least twice as long.

The saw itself is characterised by the great size of the frame, with a large gap between saw blade and the schematically drawn cross beam, the latter just a short distance away from the tensioner, allowing for deep cuts. A tall wooden post supports the saw frame by a rope fixed to the cross beam, the rope running over a pulley attached to the pole, with a counterweight at the end of the rope. The rope with the counterweight runs through a ring pulled to the side to keep it away from the stone bloc and from interfering with the saw (Fig. 18). When the operator moves the saw to and fro the counterweight may move up and down to some extend, keeping the saw blade in contact with the stone. By means of the counterweight the pressure of the saw blade onto the stone could be set to a desired value, also keeping the saw frame upright, although tilting sideways (*Verkantung*) of the blade will not be entirely prevented.

Two more posts are set up left and right of the stone bloc, a second rope running between the posts. In the middle this rope is fixed to the upper end of the saw frame (in the drawing apparently to the tensioner). An additional weight is attached to the rope halfway between the pole in front and the saw frame to keep the rope tight yet allowing for some tolerance in length. Moving the saw frame beyond the point where the second rope is fully stretched will result in vertical displacement of the saw. This 'variable swing construction' allows the abrasive material to enter in the slit beneath the saw blade.

Rotation of the saw frame along vertical axis ('Verdrehung') will not occur readily due to the great length of the blade in the saw slit. 'Verkippung' is not prevented but may be controlled by the operator (if prevention of 'Verkippung' was desired at all)[34]. Jamming of the saw blade may occur when pushing instead of pulling the blade through the saw slit. By having the saw blade mounted in the frame allowing for some tolerance so that the blade can move a bit along its length, jamming will be prevented as the blade will be pulled every half cycle, also when the operator pushes the frame. A similar provision to guarantee that the saw blades are always pulled and not pushed may be noted in a drawing by Ramelli (1588) of a horse powered multi bladed stone sawing machine[35].

A jug standing in front of the saw and some kind of container suggest that the operator added abrasive and water from time to time. In the back of Benoist's drawing the two labourers seem to operate a saw over 4 m in length supended from two poles although the drawing is too schematic to be certain. In a model of a manual operated marble saw from the Museo Civico del Marmo at Cararra, Italy, the saw is suspended from two poles with ropes and counterweights, called *uomini morti*[36]. This is also seen in an early 20th c. photograph showing two labourers, maybe at Carrara, cutting a huge block at least 4 m long and over 1 m high (Fig. 18). The saw is suspended from two poles with ropes

[34] Some degree of convexity of the saw slit caused by Verkippung may be allowed for, the operator being able to correct excessive convexity by manually reorienting the saw frame when pushing and pulling the saw.

[35] http://dmd.mpiwg-berlin.mpg.de, author 'ramelli', drawing ra134.

[36] Bruno 2002, 188, 490 fig. 207.

and counterweights over pullies. A rope running from two additonal posts in the middle is attached with a loop over both cross beam and tensioner, similar to the variable swing construction in the Benoist drawing, now with a counter weight over a pully at the post in the back[37].

Sawing slabs out of marble blocks by manual labour was thus customary in the 19^{th} and 20^{th} c. as it was in ancient times, before the water powered saw mill was invented. The width (thickness) of the slabs varied during the sawing proces depending on the dexterity of the operator, which must have left traces on the slabs as well as on the remaining blocks from which the slabs were taken. When sawn out of a block the viewing side of the slab was flattened and polished leaving irregularities and variations in thickness on the other side to a certain degree, hidden from view once incorporated in its intended construction. Apart from the suspending with *uomini morti* and the variable swing construction the manual sawing method required no system to guide the saws horizontally nor vertically.

The stone saw mill inventor's primary aim was of course substituting the labourer's hand by a machine, incorporating in his design the manual saw with its pendular system of *uomini morti* already in use. Relieved of the task of perpetually pushing and pulling the saw frame, the operator had his hands free to frequently deposit sand and water onto the slit as the machine showed no fatigue. He had also to see that the machine worked properly and that the saw blades progressed downward in a straight line as good as could be, still a tedious task, redirecting the vertical progress of the saw blade if required, which must have left traces on the blocks. The left block at the Ephesos mill shop shows such traces, indicating a sideways repositioning of the saw blades near the lower end of the cut, while the surface of the block appears concave to some degree from top to bottom (Fig. 20). This is an indication that the early machines, at least unto and in Byzantine times, had no guiding system, and that the Ammianos relief, with its vertical saw frames while not showing details of a pendular system, depicts a realistic situation.

Discussion

For the history of stone sawing machines archaeological findings in the Anatolian Mediterranean are of great importance. First is the recent discovery of the relief of a water-powered twin stone saw mill on the cover of a sarcophagus at Hierapolis (Pamukkale), 3^{rd} c. AD. Then there are the remains of a 6^{th}-7^{th} c. stone saw mill studio at Efesos, paralleled by a similar finding at Gerasa (Jordan). From these findings it is evident that the Romans applied water power to drive stone sawing machines, transforming the rotary movement of the water wheel into a reciprocal linear movement by means of the crank and connecting rod system, previously thought to be a medieval invention. The findings have led to a number of reconstructions of the ancient sawing machines which are discussed above. All reconstructions envisage the crank and connecting rod system, but all differ on technicalities of the saw frames and of the guiding system for the saw blades.

Of the reconstructions, only the reconstruction of the Ephesos mill, by Fritz Mangartz, has no guiding system. Mangartz proposes horizontal saw frames for easier mounting of

[37] Visible in enlarged photograph.

the blades and for the fact that the center of gravity of the frame lies along and not above the saw blades, thought to reduce the risk of misalignment. Yet vertical frames cannot be excluded for Ephesos. Mangartz discusses the principle of pendular saws referring to publications by Warnecke stating that the saw frame will move up and down continuously when pushed and pulled to and fro, contacting the stone for a short distance of the swing only even if the ropes are relatively long. The up and down movement of the saw would indeed guarantee that the mixture of abrasive and water deposits underneath the saw blade required for efficient sawing. As shown above a pendular system with vertical saw frames, and with *uomini morti* and the variable swing construction may be considered an alternative, as it guarantees that the saw blades remain in contact with the block each stroke for a substantial distance, until the ropes tighten and the saw blade is shortly lifted from the stone bed allowing the abrasives to deposit underneath the blades.

The Gerasa reconstruction by Jacques Seigne resembles the Hierapolis situation for its vertical saw frames. The absence of counterweights for the heavy frames that Seigne envisages, however, does not readily allow for the lifting of the saws needed for the abrasive material to enter underneath the blades. The heavy saws also require sturdiness of the guiding frames that Seigne thinks necessary, and strong and therefore heavy cranks and connecting rods (for which counterweights are now thought necessary), contrasting the manual saws that a single man must have been able to operate sawing marble blocks of similar size as found in the Gerasa work shop, be it one cut at a time. Although the Gerasa multiple blade system does require a wider and thus heavier frame, reducing size and weight as much as possible and adding compensating weights may be an issue. Future experiments planned at Gerasa may resolve this matter.

The reconstruction of the Hierapolis stone saw mill by Klaus Grewe, with both vertical and horizontal guiding of the saws, refers to a machine proposed in 1718 by the German engineer Sturm. The Sturm machine indeed prevents all misalignments of the saw blade and will produce flat cuts. However, Sturm himself claims that he *invented* the machine because he had seen saw mills that in his opinion did not function properly. Inventing a system that would have already been in use for one and a half millenium, since Ammianos' time, does not quite seem a realistic situation. Sturm obviously invented a machine that was not known before.

When the Ammianos machine is imagined with light weight vertical frames, and with a system of *uomini morti* and variable swing construction as for manual saws, guaranteeing both lifting of the saw frame each half cycle as well as preventing, together with the skilfulness of the labourer, misalignments of the saw blades, a realistic and practical model of the Hierapolis water powered stone saw mill, and later mills, may be envisaged.

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Öz

Anadolu Akdenizi'nde Roma ve Erken Bizans Dönemlerinde Taş Kesme Makineleri

Pax Romana zamanında, imparatorluk genelinde refah düzeyi yükseldiğinde kent yaşamının standart elemanları haline gelen kamu ve özel hamamların suyunu getirmek için hemen hemen her kentte sukemerleri inşa edildi. Bu hamamların ve diğer yapıların duvarları, Antalya civarında da yoğun şekilde görüldüğü üzere mermer ile kaplandı. Söz konusu mermer levhalar giderek artan miktarlarda üretilmiş olmalıdır. Anadolu Akdenizi'ndeki yeni bulgular su ile çalışan taş kesme makinelerinin daha Roma Dönemi'nde bilindiğini gösteriyor. Phrygia Hierapolisi'nin (Pamukkale) kuzey nekropolisindeki bir lahit kapağı üzerindeki kabartmadaki teknik desende, sıra dışı bir şey, su ile çalışan taş kesme makinesi betimlenmiş. Değirmen şimdiye dek Ortaçağ'da icat edildiği düşünülen krank ve krank kolu sistemine sahiptir. Krank ve krank kolu sistemi, su çarkının döner hareketinin, ters lineer harekete dönüştürülerek mermer levhaların toplu üretiminin yapılmasını sağlar.

Erubris (Ruwer) Irmağının sularıyla çalışan mermer kesme makineleri ve tahıl değirmenlerinin sesini Ausonius, İ.S. 370 civarında kaleme aldığı *Mosella* adlı şiirinde şöyle betimliyor: "Taşları, baş ileride döndüren ve gıcırdayan testereleri pırıldayan mermerden geçiren Erubris, her iki yakasında da sürekli gürültü dinliyor." Bu şiir zaten testere makinelerinin daha Roma döneminde var olduğuna dair kanıt sayılıyordu fakat 1960'larda krank ve krank kolu sisteminin Roma Dönemi'nde var olamayacağı kanaatine varılınca *Mosella* şiirinin aslında 10. yy.'da tahrif edildiği düşünülmüştü. 1980'lere gelindiğinde bu düşüncenin yanlış olduğu kanıtlandı ve aslında şiirin orijinal olduğu anlaşıldı. Yine de kanıt mevcut olmadığından Romalıların krank ve krank kolu sistemini bildikleri bir türlü tasavvur edilemiyordu; Ausonius'un şiirini karşılayabilecek dairesel testere veya sürekli tel testere gibi alternatif mekanizmalar önerildi ki, bunların hepsinin ciddi teknik sorunları bulunuyor. Hierapolis'teki kabartma artık, Romalıların krank ve krank kolu sisteminin bildiklerini ve taş kesme makinelerinde bu sistemi kullandıklarını, 4. yy.'da Ausonius'un Alplerin kuzeyinde suyla çalışan makinelerle mermer kesilmesi sesini doğru bildiğini açıkça gösteriyor.

Ephesos'taki iki paralel bıçaklı taş kesme makinesine ait kalıntılar ve Gerasa (Ürdün)'deki dört bıçaklı benzer bir makine 6. ve 7. yy.'lara tarihlenmekte olup bu makinelerin Hierapolis örneğinden sonra oldukça gelişmiş olduğunu gösteriyor. Hierapolis kabartması ile birlikte Bizans Dönemi'ne ait bu bulgular sayesinde, bu yazıda irdelenen bir dizi antik taş kesme makinesi rekonstrüksiyonları geliştirildi. Tüm rekonstrüksiyonlarda krank ve krank kolu öngörülmekte ancak testere çerçevelerinin ve testere bıçaklarının kılavuz sistemlerinin teknik özelliklerinde farklılıklar vardır. Kesme makineleri için testere bıçaklarının monte edileceği çerçeveler düşey veya yatay olabilir. Hierapolis kabartmasında bu çerçevenin düşey olduğu kesin ancak Ephesos ve Gerasa'dan Bizans Dönemi örneklerindeki çerçeve tipleri belirlenemiyor. Bu antik kesme makineleri için hem düşey hem de yatay çerçeveler öngörüldü. Üstelik bazı bilim adamları kesimlerin düzgün olabilmesi için testere çerçeveleri için bir tür kılavuz sisteme gerek olduğunu düşünüyor.

Almanya Römisch Germanisches Zentralmuseum'dan Fritz Mangartz'ın 2009 yılında önerdiği Ephesos makinesi rekonstrüksiyonunda bıçaklar için kılavuz sistem bulunmuyor. Mangartz, bıçakların daha kolay monte edilebilmesi ve de çerçevenin ağırlık merkezinin testere bıçaklarının yukarısında değil de üzerinde olup daha iyi hizalama için yatay çerçeveler öneriyor. Yatay testere çerçeveleri dört köşesinden makara üzerinden karşı ağırlıkla iplerle asılıyor. Mangartz, ipler yeterli uzunlukta ise ileri geri itildiğinde testere çerçevesi yukarı aşağı hareket ederek taşa yalnızca kısa ama yeterli mesafede temas ettiği sarkaç testere ilkesini irdeliyor. Testerenin yukarı-aşağı hareketi ile etkin kesme işlemi için gerekli olan, bıçağın altında aşındırıcı ve su karışımının birikmesi sağlanır. 2010 yılındaki bir yayınında ise Mangartz, rekonstrüksiyonunun 1:1 ölçekli maketi ile yaptığı deneyleri irdeliyor.

Fransa CNRS/Tours Üniversitesi'nden Jacques Seigne tarafından yapılan Gerasa makinesi rekonstrüksiyonunda, Hierapolis örneğine benzer şekilde dört paralel bıçak, düşey çerçeveye monte edilmişti. Orijinal konumda 1:1 ölçekli rekonstrüksiyon 2007 yılında gerçekleştirildi. Mangartz'ın aksine Seigne karşı ağırlık kullanmadı. Fakat Seigne'in öngördüğü ağır testere çerçeveleri, aşındırıcı maddenin bıçakların yükselerek bıçakların altına girmesine fırsat vermiyor. Seigne, düşey testere çerçevelerinin düz bir hat boyunca ilerleyebilmesi için basit ahşap kılavuz çerçeveler öngörüyor. Ağır testereler için dayanıklı ve güçlü kılavuz çerçeveler gerekli ve dolayısıyla da ağır kranklar ve krank kolları gerekli (artık bunlar için karşı ağırlıkların gerekli olduğu düşünülüyor). Bu durumda asırlardır bilinen ve bir veya iki adamla çalıştırılabilen, Gerasa atölyesinde bulunanlara benzer ebatlarda taşları kesebilen, sarkaç tipi ve karşı ağırlıklı manüel taş testereler ile tezat ortaya çıkıyor. Yukarıda sözü geçen makalede Gerasa çok bıçaklı sisteminde daha gelişkin ve de dayanıklı düşey bir çerçeve gerekmesine karşın ebatları ve ağırlığı mümkün olduğunca azaltmanın ve karşılayıcı ağırlıklar eklemenin hayati bir önemi olabilir. Gerasa'da yapılması öngörülen yeni deneyler bu konuyu açıklığa kavuşturabilir.

Hierapolis taş kesme makinesiyle ilgili olarak Almanya Bonn'dan Klaus Grewe tarafından önerilen üçüncü bir rekonstrüksiyon ise hem yatay hem de düşey kılavuz sistemine sahiptir. Grewe 1718 yılında Alman mühendis Sturm tarafından önerilen bir makineye atıfta bulunuyor. Çerçevelerden biri, üzerine kesilecek bloğun yerleştirildiği platform üzerine sabitlenen bir tür ray sistemi üzerinde yatay hareket edebilen, tekerlek veya benzeri bir düzeneğe sahiptir. Bu taşıyıcı, su çarkıyla hareket eden bir krank ile krank kolu sayesinde itilip çekiliyor. Testere bıçaklarıyla donatılan ikinci bir çerçeve ise tekerlekli çerçeve içinde aşağı yukarı hareket ediyor. Grewe, Hierapolis makinesi için de benzer bir sistemin uygulanmış olması gerektiğini öne sürüyor. Gerçekten de böylesi bir makine bıçağın yanlış hizalanmasını önler ve düzgün kesimler yapılmasını sağlar. Ancak, Sturm bu makineyi kendisinin icat ettiğini çünkü gördüğü bazı kesme makinelerinin düzgün çalışmadığını öne sürmüş. Ammianos'un zamanından beri, 1500 yıldır kullanımda olan bir makineyi icat etmek pek akla yatkın gelmiyor. Görünen o ki, Sturm daha önce bilinmeyen bir makineyi icat etmiş.

Antik Dönem'den 19. yy., hatta 20. yy.'ın başlarına kadar bilinen yöntemde bir veya iki adamla kullanılan, dört metreye kadar hatta daha uzun dişsiz bıçağı olan, makaralar üzerinden karşı ağırlıklar yoluyla dengelenen ve iplerle asılan düşey testerelerle büyük bloklar kesilebiliyordu. Eğer Ammianos makinesi düşey çerçeveler ve manüel testerelere göre karşı ağırlıklı bir sistemle öngörülür, aşındırıcı maddenin bıçağın altında birikeceği şekilde çerçevenin kalkmasını sağlarsa, işçi, testereyi sürekli ileri geri hareket ettirme, bıçağın altına su ve aşındırıcı madde ekleme, testerenin hizasını sürekli kontrol etmeyi kapsayan işinde rahatlar; ve böylece Hierapolis kabartmasında görülen, su ile çalışan taş kesme makinesi ve daha sonraki makineler için gerçekçi ve pratik bir model öngörülebilir.

Tab. 1 Aspects of reconstructed stone sawing machines

	Saw frame	Guiding frame or - system	Weights
Hierapolis/Kessener	vertical	vertical	----
Gerasa/Seigne	vertical	vertical	no
Ephesos/Mangartz	horizontal	none	yes
Hierapolis/Grewe	complex	vertical/horizontal	additional weights

Fig. 1
Relief of marble studio with 2 marmorarii showing their manual stone saw, saw blade upward.
Ostia, late Flavian (Olivanti 2002, 499).

Fig. 2a
Hierapolis relief (photo P. Kessener).

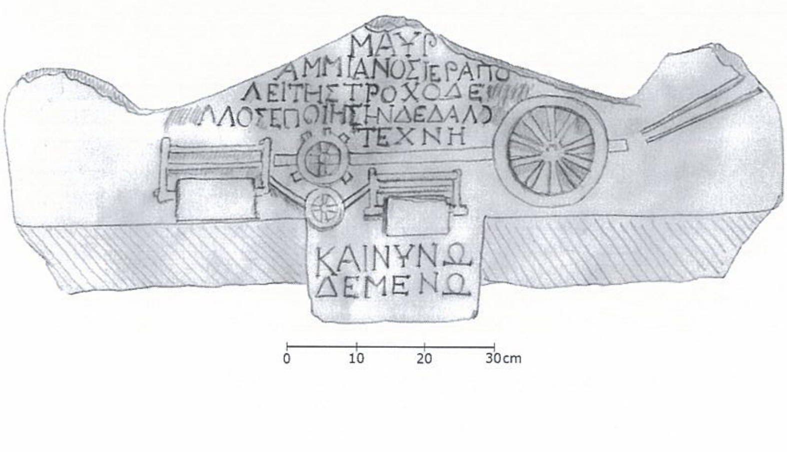

Fig. 2b
Copy of the Ammianos inscription and relief (courtesy T. Ritti).

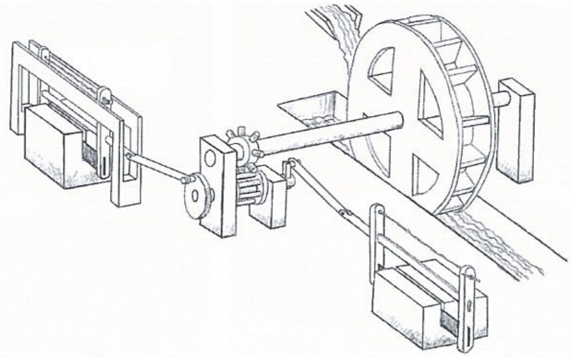

Fig. 3
Preliminary reconstruction of the Hierapolis mill (P. Kessener).

Fig. 4
Gerasa, Room in cryptoporticus of temple of Artemis, back wall with remains of head race, mill race and walls supporting wheel's shaft, in front the tail race, in the floor and covered with stone slabs (courtesy J. Seigne).

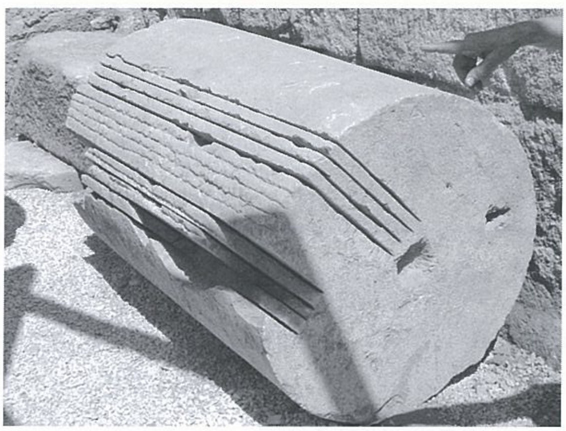

Fig. 5
Gerasa, stone drum with four parallel saw slits (photo G. Wiplinger).

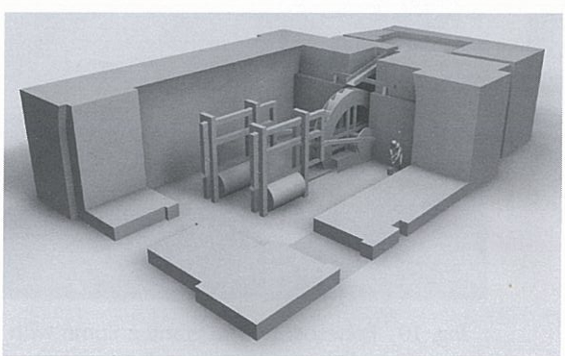

Fig. 6
Gerasa, reconstruction of stone saw mill (courtesy J. Seigne)

Fig. 7a/b Remains of Ephesos stone saw mill, in Hanghaus 2. Right: two parallel saw slits in stone bloc (rear end of left bloc); the left saw blade was put to sawing before the second blade resulting in a difference in depth of the slits of 1-2 cm (photo's P. Kessener).

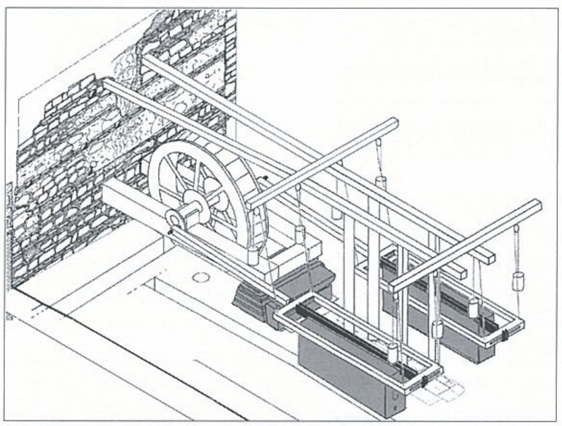

Fig. 8
Reconstruction of Ephesos saw mill by Mangartz (courtesy F. Mangartz).

Fig. 9 Ephesos, stone weight with remains of iron ring (courtesy F. Mangartz).

Fig. 10 Ephesos, 2.35 m granit column with twe parallel saw slits (photo P. Kessener).

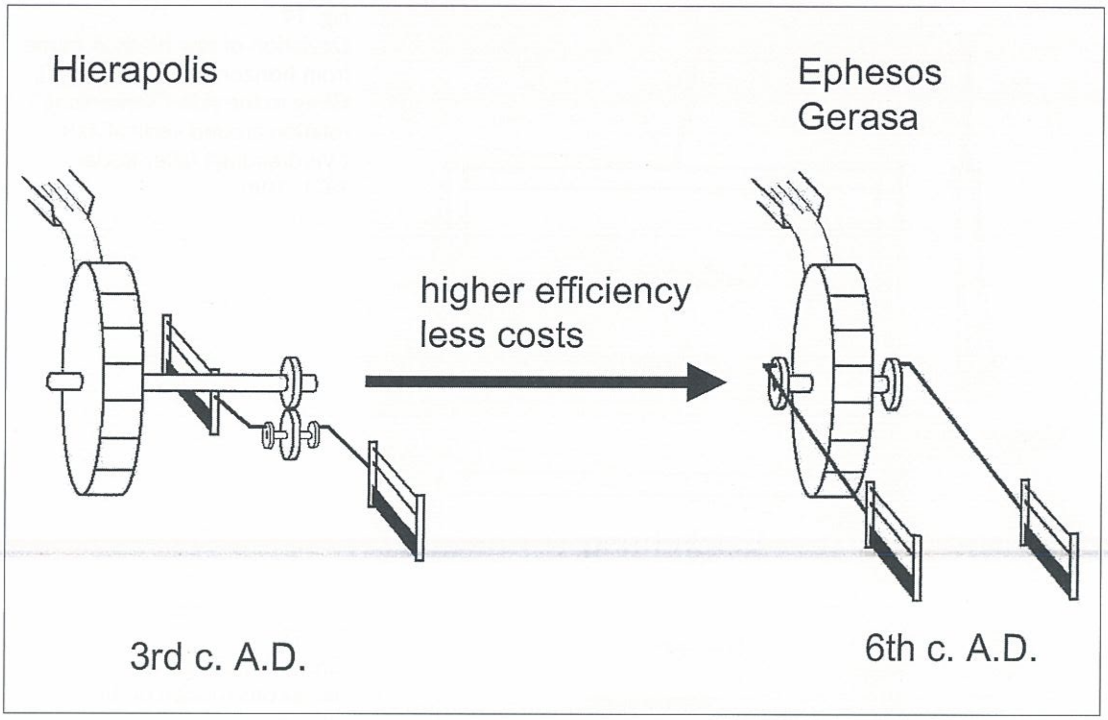

Fig. 11 Development of stone saw mill (P. Kessener).

Fig. 12 Reconstrustruction of the Ephesos sawing machine by Mangartz, with horizontal saw frames and two parallel saw blades (courtesy F. Mangartz).

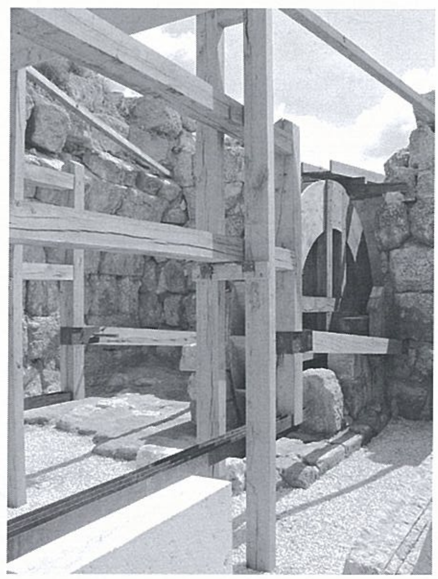

Fig. 13 Seigne's reconstruction of the Gerasa sawing machine, put up at the original location, with water wheel, vertical saw frames with four parallel saw blades, and guiding frames (photo G. Wiplinger).

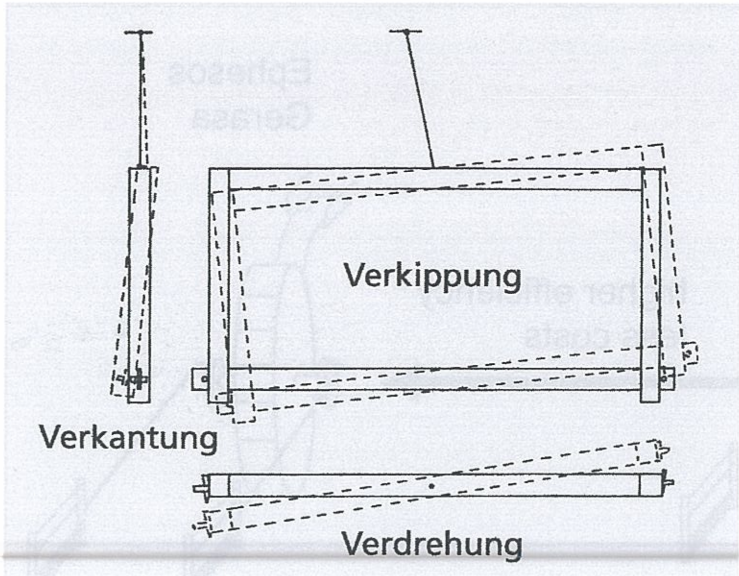

Fig. 14
Deviation of saw blade & frame from horizontal ('Verkippung'), tilting to the side ('Verkantung'), rotation around vertical axis ('Verdrehung') (after Röder 1971, 308).

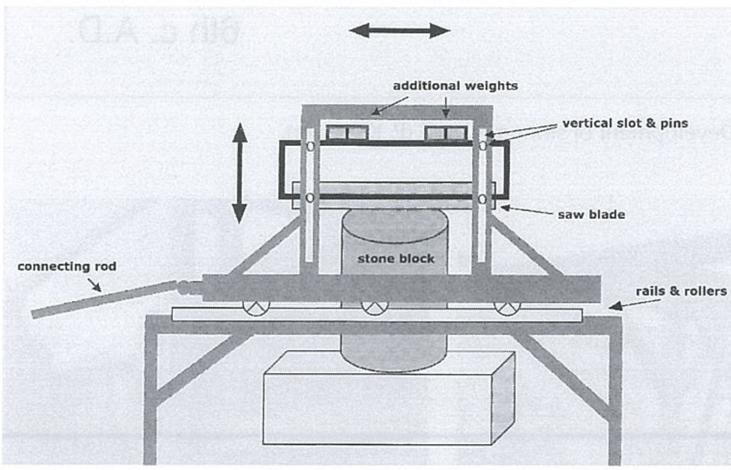

Fig. 15
Grewe's proposal for the reconstruction of the Hierapolis sawing machine (after Grewe 2009, 451).

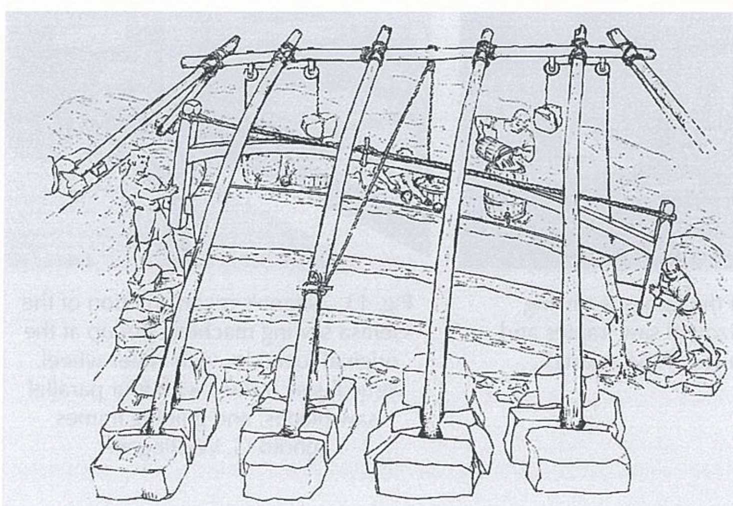

Fig. 16
Reconstruction of pendular saw for cutting large blocks out of the rock, by Röder (Röder 1971, Fig. 64).

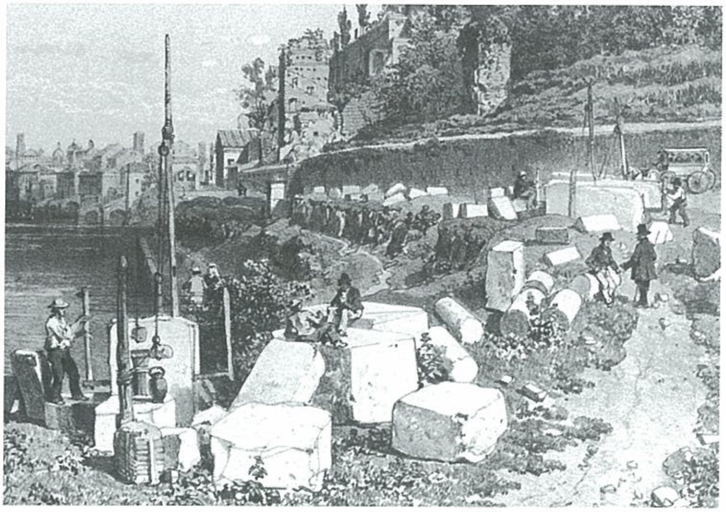

Fig. 17 Part of 19th c. Benoist drawing showing manual sawing at the Marmorata, Rome (courtesy M. Maischberger).

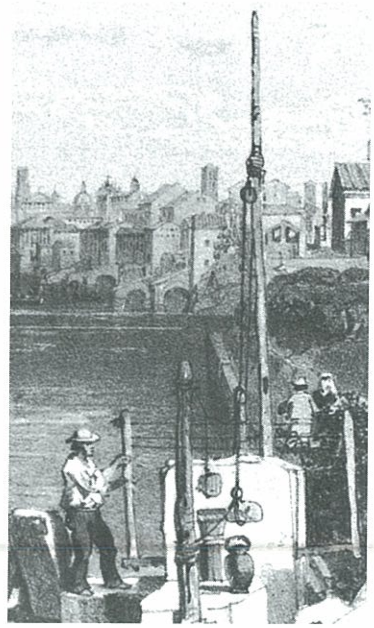

Fig. 18 Detail of Benoist drawing.

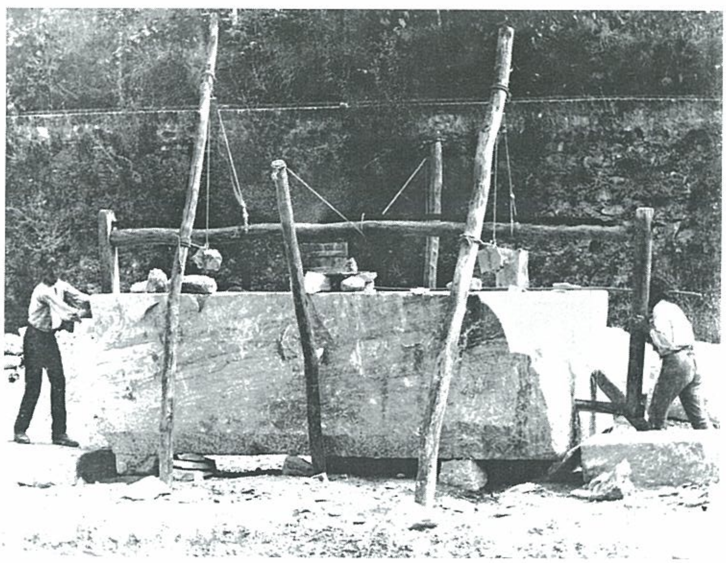

Fig. 19 Early 20th c. photograph with two labourers operating a manual saw suspended from two poles with ropes and counter weights (courtesy G. van Leeuwe).

Fig. 20 Ephesos stone saw mill. Traces of repositioning of saw blades on left stone block.