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Evidence for Use of a Stone-Cutting Drag Saw by the Fourth Dynasty Egyptians

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Of the temple that adjoined the east face of Khufu's Pyramid, only a portion of basalt paving remains. Though continually ravished by hoofs and wheels, being part of a modern service-road, these blocks allow a concentrated study of the method used for cutting hard stones in the Old Kingdom.

Some of these blocks have been *incised* by a means, and for a purpose, not immediately clear. Similar incisions can be seen[1] in other places, but those are relatively isolated and not as informative as the variety of cuts we see in Khufu's temple pavement.

The greater portion of paving blocks form a contiguous group about fifteen meters east-to-west and twenty-five meters north-to-south, the latter axis followed by the road previously mentioned (fig. 1). Other paving blocks lie scattered nearby. Because of block removal/displacement, the main group has a very irregular border, especially along its east and west boundaries. According to Petrie,[2] only about one-fourth of the temple pavement remained *in situ* in 1883. Today these edges continue to break down under the action of traffic and are extensively repaired with concrete.

The result is that even though the vertical sides of many of the east and west perimeter blocks are visible, most are no longer *in situ.* Those blocks considered to be *in situ,* including several that are separated from the main group, are so judged because they are bonded to either bedrock or, more typically, limestone shims, with mortar that looks similar to the pink gypsum mortar[3] used at Khufu's southern boat pits and which can be observed in the lower courses of core masonry of his pyramid.

Description of the Paving Blocks

The paving blocks are formed of dark-gray pyroxene diabase,[4] a rather coarse-grained basalt. For the sake of brevity this paper will use the nomenclature of previous references in calling this material simply *basalt.* According to Professor Dietrich Klemm,[5] the source of this stone was at Gebel Qatrani, north of the Fayum.

The blocks vary considerably in size. The largest block, henceforth called block A, lying alone a few meters east of the center of the main group, is about 1.50 m square and 50 cm thick (fig. 2). Most blocks, however, are not more than

[1] W. M. F. Petrie, *Tools and Weapons* (London 1917), 44; S. Curto, *Gli Scavi Italiani a El-Ghiza (1903)* (Rome, 1963), 73, fig. 27-a.

[2] W. M. F. Petrie, *The Pyramids and Temples of Gizeh,* 2nd ed. (London, 1885), 15.

[3] M. Z. Nour, Z. Iskander, M. S. Osman, and A. Y. Moustafa, *The Cheops Boats* (Cairo 1960), 31, give the following analysis of the coarse mortar that was used in conjunction with the limestone beams that covered the eastern member of the two boat pits on the south side of Khufu's Pyramid: "The mortar . . . is coarse and pinkish white. Chemical analysis showed that it is mostly composed of calcium sulphate and contains some silica, iron and aluminum oxides, calcium carbonate, sodium chloride and magnesium carbonate."

[4] R. Hamilton, Senior Research Physicist, Manville Service Corp., Denver, Colorado, using optical microscopy and x-ray diffraction, examined two samples of this stone for the author in June 1989. Excerpts from his analysis are appended to this paper.

[5] D. D. Klemm, Ludwig-Maximilians-Universität, Munich, Institut für Allgemeine und Angewandte Geologie, in a letter to the author dated 9 March 1989, states " . . . I would like to help you in any respect as far as the basalt pavement blocks of Khufu's mortuary temple is concerned. This material comes without doubt from Gebel Qatrani, north of the Fayum."

Fig. 1. View of pavement from southeast. Photograph by Sheri L. Moores.

Fig. 2. Block A, from east.

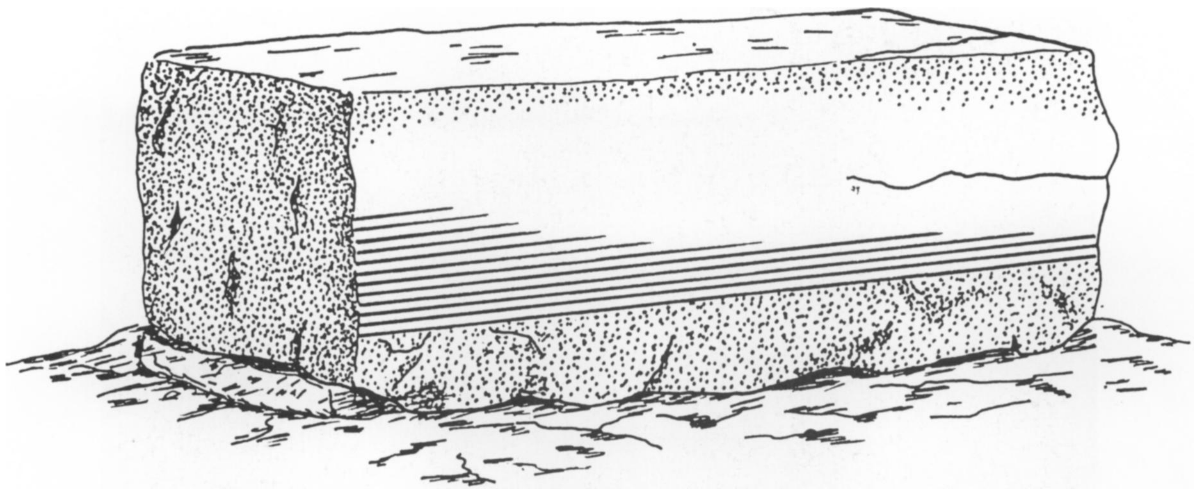

Fig. 3. General disposition of striations.

70 cm across and, where visible, 40 cm thick. In plan the blocks are nearly square. A few have notched corners that receive adjacent blocks. The joints between blocks rarely exceed three millimeters in width.

Surface conditions distinctly differ between the tops, sides, and bottoms of the paving stones. The tops are fairly flat, but rounded at the edges, giving the smallest blocks the look of cobble stones. Though dotted with shallow craters and traversed with fracture lines, the top surfaces are otherwise smooth and worn, making them obtrusive, even on displaced blocks.

The few bottom surfaces that are visible are very rough and uneven, apparently broken from other pieces. The block sides are typically flat, but rough textured, with the appearance of being hammer-dressed; that is, the surface is comprised of an irregular spacing of small (impact?) craters that give the entire face a regular aspect.

An unusual feature of the block sides provides the impetus for this study. Of block sides that one can observe, a small portion (less than ten percent) possess striated areas that have been attributed[6] to the action of some sort of saw. It is the purpose of this study to determine how these marks were made—and why.

Description of the Cut Marks

The incised areas are very irregular in profile, block to block, and comprise not more than three-fourths of the total area of any face, usually much less. The remainder of the face is hammer-dressed. The incised area is typically on the lower portion of a block face, and appears as a generally-flat patch traversed by striations that become progressively more distinct with distance from the upper border of the cut toward the lower, and from the middle of a face toward its sides (fig. 3). A few incised patches appear so ground that striations cannot be detected.

The striations are essentially-parallel grooves up to a half millimeter deep, spaced about one to two millimeters apart (fig. 4). In cross-section the grooved face would approximate a sine curve, with the valleys being slightly narrower than the lands between. On most cuts the striations follow straight lines, but on one example the straight scratches that traverse the face sweep

[6] W. M. F. Petrie, op. cit., 14 and 75; S. Clarke and R. Engelbach, *Ancient Egyptian Masonry* (London, 1930), 204; A. Lucas, *Ancient Egyptian Materials and Industries*, 4th Ed. (1962), 69–72; V. Maragioglio and C. Rinaldi, *L'Architettura Della Piramidi Menfite*, IV (Torina and Rapallo, 1965), 60.

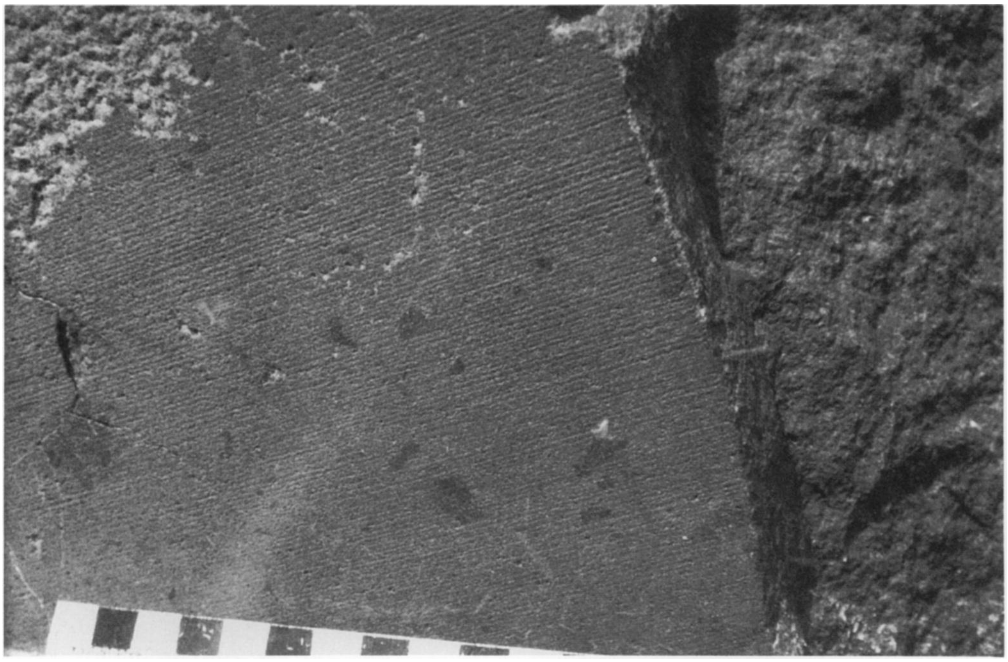

Fig. 4. Close-up of striations.

Fig. 5. Plunge cuts in block B. Photograph by Sheri L. Moores.

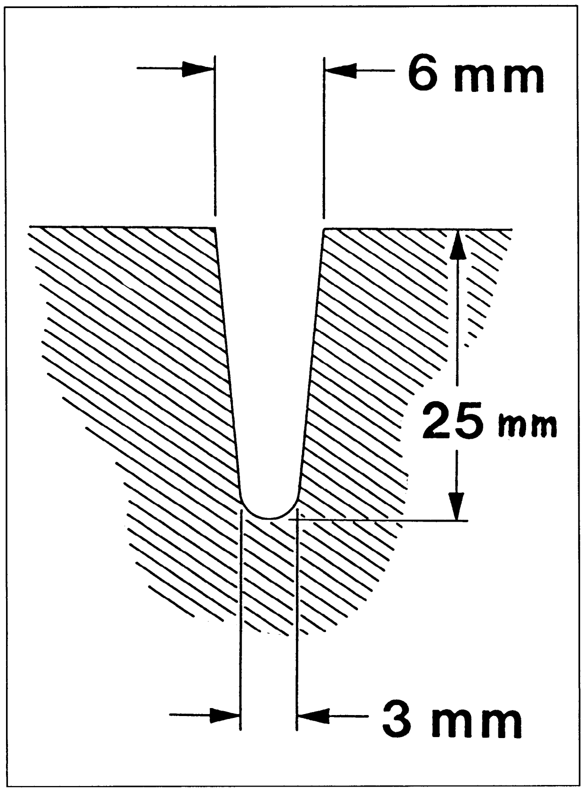

Fig. 6. Cross-section of plunge cut.

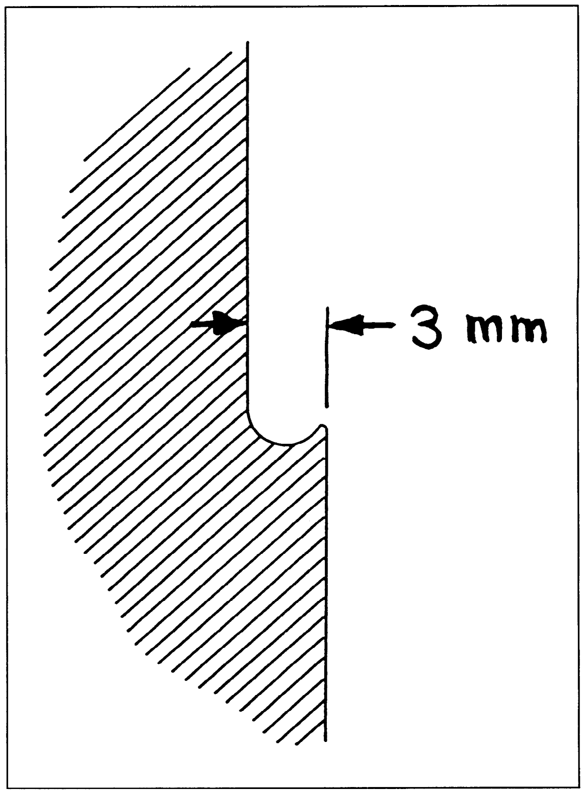

Fig. 7. Step-cut profile of block A face.

away from the bottom of the cut with a radius of about two meters. This sweep-out occurs within the last twenty centimeters at only one end of the cut that is in total about one meter long. It should be noted that adjacent grooves in the sweep-out portion vary somewhat in radius.

Two blocks were observed to have plunge cuts that indeed indicate the action of a saw blade. Otherwise, we could not rule out the production of the flat-face marks by a surfacing, e.g., filing, tool. Three near-vertical plunge cuts on block B, located at the southeast edge of the pavement, are nearly parallel and almost equally spaced, about three centimeters apart (fig. 5). Their bottoms are in the same plane and reach a maximum depth of about 25 millimeters. In cross section the kerf, i.e., narrow slot that the blade makes while cutting, has, by eye, a perfectly radiused bottom, about three millimeters wide, that tapers outward with an included angle of about eight degrees (fig. 6). The kerf sides are very smooth—not striated.

It is not definite that the blade that made these cuts was wedge-shaped in section, since it might have wobbled as it cut. However, it was certainly not thicker than three millimeters at its tip. By modern standards this is unusually narrow for a stone sawing blade of the size needed for this type of work. Block B is *in situ*, as are several others which have stepped cuts that display the same blade tip radius of 1.5 millimeters (fig. 7).

The Purpose of the Saw Cuts

A determination of *why* the saw cuts were made might help in discovering *how* they were made, but the purpose for these cuts is not obvious. Petrie said, "the blocks of basalt are all

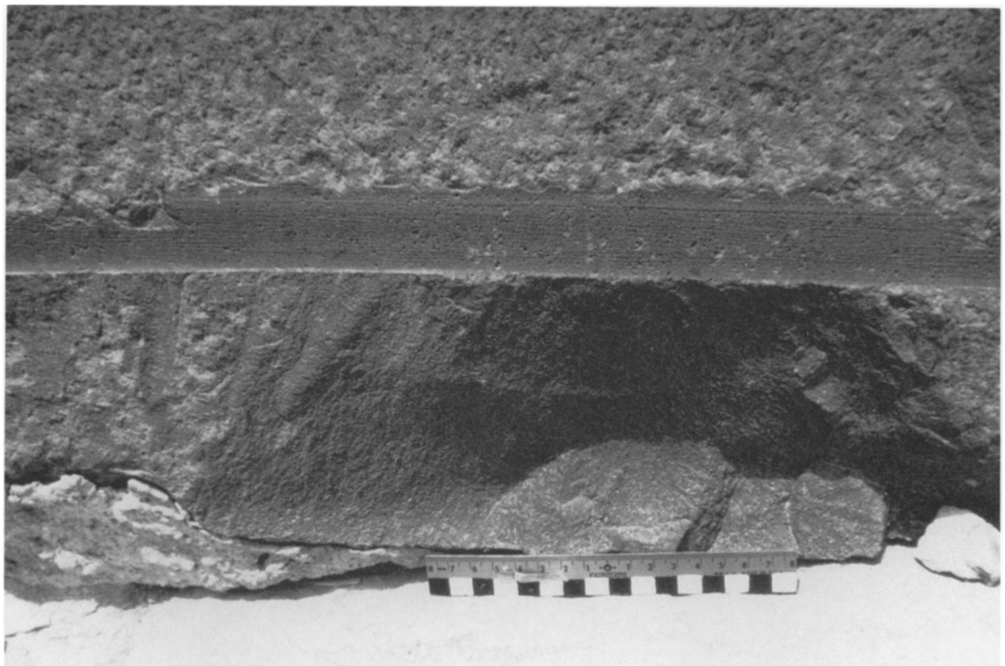

Fig. 8. Splayed face of block C.

sawn and fitted together."[7] Though it would be presumptuous to interpret this as meaning that he thought the blocks were sawn for the purpose of fitting, it is puzzling that the vast majority of these stones visible today have no saw marks. Maragioglio and Rinaldi likewise imply that the sawn blocks predominate, but suggest that the saw cuts were made to facilitate block division, and that the hammer-dressed areas represent final trimming for close fit.[8]

[7] W. M. F. Petrie, ibid., 14.

[8] V. Maragioglio and C. Rinaldi, ibid., 60: [The basalt blocks of Khufu's pyramid temple] "were almost entirely sawn through and then the break was completed by a stroke of a sledge hammer. The saw cuttings were not made vertically but almost always slightly slanting. In some blocks the resulting sharp upper edge was then adjusted by hammering, evidently in order to obtain thin and well made joints between the blocks. In others, where the sawn part slanted outward, the whole face was straightened by hammering. In one case we noted saw cuts made in two opposite sides of a block. The cuts were both slanting and did not coincide in the middle of the block: the part between the saw cuts was irregularly fractured and in this particular case the face was not regularized by hammer strokes."

The two differing views as to the purpose for the cuts, block division and trim fitting, lead to the question: Which came first—sawing or hammering?

Examining the sequence issue first, it can be observed that in most cases the saw only slightly shaved a face that had already been made fairly flat, but rough-textured, by hammer-dressing. The blade started cutting at a certain point on the block face and increasingly flattened peaks as it progressed. In the same progression the distinct but irregular impact-formed craters are gradually reduced to smaller and smaller pockets, eventually disappearing toward the bottom of the cut. It is analogous to an unevenly-worn automobile tire, where enough tread pattern exists in worn spots that the original shape can be deduced. If hammer-dressing was done after the sawing operation, as Maragioglio and Rinaldi suggest, why can one see remnants of hammer-picking within the sawn areas? Why doesn't the hammering stop at the border of the saw cut? Another argument against this sequence is the extreme scarcity of sawn faces. Hammered faces are the rule. If anything represents final trimming, it is the sawn areas. Thus, it seems more likely that the saw marks were made after the hammering.

Now to the reason for the saw cuts. Sawn faces are so atypical that the blocks must have been obtained in nearly final form, perhaps from loose boulders, and then squared by hammering. In no case is it apparent that one block was separated from another by sawing, or that a shallow saw cut was used to guide the subsequent splitting of a block. On only one sawn face, block C (fig. 8), is it apparent that a chunk of material has been splayed from the bottom of the saw cut, and this fractured area, in the bottom center of the face, is so small it seems hardly worthy of the saw cut that traverses the entire block. Block division is therefore an unlikely purpose for the saw. If division *was* necessary, some other method was presumably used. However, no wedge slots of the type seen on granite workings are visible anywhere.

Trimming for closer fit is a possible reason for some of the saw cuts, but does not satisfy all cases. On *in situ* blocks, hammer-dressed faces abut at their upper edges, the joints widening somewhat toward the interior (fig. 9). In one of these joints a sawn area on one block is of such slight depth and great separation (more than 1 cm) from its neighbor that it is difficult to understand how its omission could have affected the fit. The same can be said for several other examples where the sawn area is a shallow concavity in the middle of a flat, hammer-dressed face.

There *are* several places where the saw might have been needed for final trimming. On the eastern face of block A the cutting angle was changed several times as it worked around a protrusion at the lower left corner (fig. 10). The protrusion has been roughly shaped by hammering, but the hammering stopped at the point where a major crack appears. The crack runs diagonally into the block such that continued hammering might have caused a large portion of the block to flake away. On this block, and several other flawed stones, the saw might have been used for a final trim to prevent possible injury from further hammering.

Fig. 9. Joint showing sawn area on in situ block.

A possible explanation for the sawn blocks that are *not* flawed is that these were not the object of the saw. Perhaps the saw marked these blocks while it was cutting something else. The circumstance that would make this reasonable will be explained in the next section.

The Configuration and Action of the Saw

The progressive smoothing toward the middle of the block face suggests that cutting occurred not only at the blade tip, but also on its sides. Two inferences can be drawn: The blade was fairly deep, probably greater than 40 cm; and

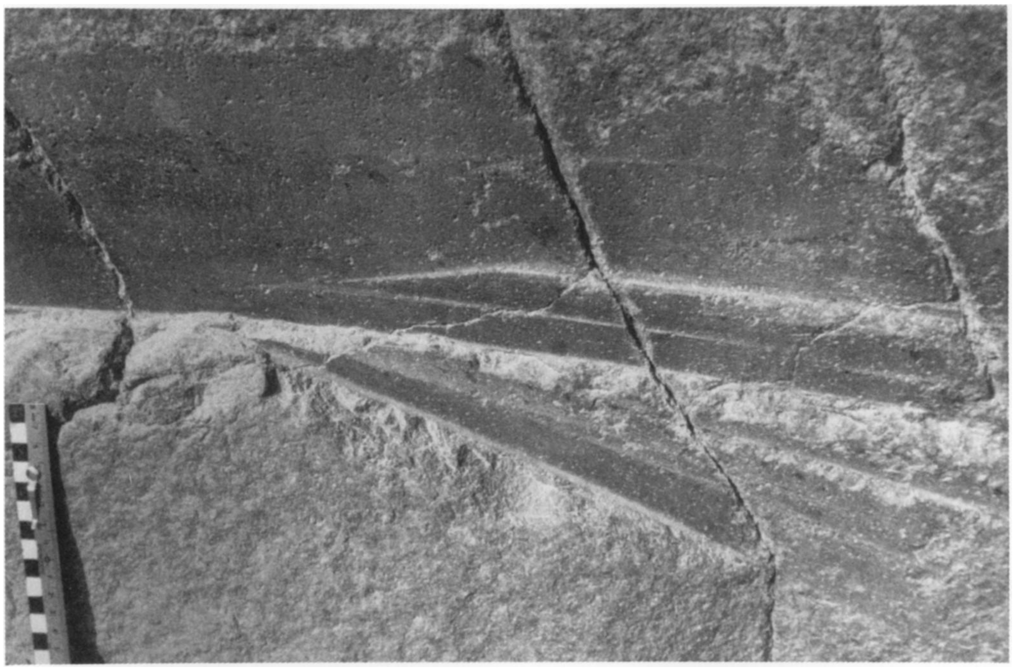

Fig. 10. Close-up of eastern face of block A.

it probably effected cutting with a loose, fine-grained abrasive medium rather than a jewel-set edge. We would not expect a jewel-set blade, i.e., one having raw diamond or corundum stones cast into, or otherwise affixed to, its cutting edge, to progressively remove the scratches it creates at the cutting lip as it advances.

The cut grooves could not have been produced by a rotating blade such as found on a circular saw. A rotating blade does not make scratches of variable radius. Even if the blade was four meters in diameter we would expect to see a pattern of circular scratches across the cut face of two meters radius, but this is not the case. The only other uni-directional cutting means that is at least feasible is an abrasive-fed cable or band saw, but the degree of mechanization needed for these devices does not fit well in the Fourth Dynasty of ancient Egypt. The remaining possibility is that these scratches were produced by a reciprocating straight blade. In fact, the type of grooving we see *is* known to be produced by a reciprocating, abrasive-slurry-fed blade having a notched edge.[9]

[9] O. Bowles, *The Stone Industries* (New York & London, 1934), 57.

The arrangement just described is a good fit for the saw marks that appear on Khufu's basalt paving stones. This type of saw, called a *drag* or *frame* saw, has been used to cut soft and hard stones for centuries, and is reported to date to at least 300 B.C.[10] In its modern configuration as a slab-making machine, multiple blades are clamped in a frame and adjusted apart to the desired thickness of the finished slab. The frame hangs from four bars that connect its corners to an elevating (feed) mechanism above. According to Bowles, "as the frame moves back and forth, actuated by a crank and connecting rod (pittman), the cutting blades lift toward the end of each stroke. This permits sand to wash under them, and as they start back on the return stroke the blade bears on the sand which abrades the stone rapidly."[11] When sand was used as the cutting agent the preferred blade material was soft iron or steel. The sand would embed itself in the metal and have less tendency to erode the blade. Sand was eventually replaced by chilled iron shot, then steel shot, and finally by tungsten-

[10] G. P. Merrill, *Stones for Building and Decoration* (New York, 1891), 344.

[11] Bowles, 57.

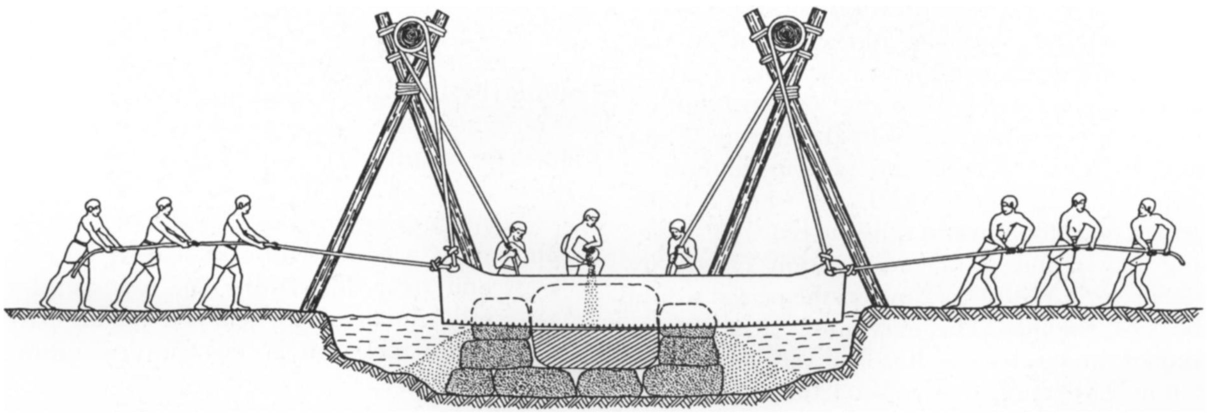

Fig. 11. Operation of the 4th Dynasty drag saw.

carbide pellets, as the abrasive for cutting granite.

One might imagine a less-developed version of the drag saw that is more in harmony with the technology, as presently understood, of the Fourth Dynasty Egyptians. This hypothetical variant had a single copper blade about four meters long and 60 centimeters broad. The blade section was wedge-shaped, tapering from one centimeter at its back to three millimeters wide at the cutting edge (fig. 11). This geometry yields a blade weight of about 140 kg. The cutting edge was straight, but notched. The blade was suspended by ropes attached to its ends. The other ends of the ropes were passed once around horizontal beams so the blade could be fed into the work by relaxing tension.

Perhaps a finer adjustment means was used, but in any case the actual feed rate was probably determined by gravity. That is, once the swinging blade made contact with the work, it guided itself across the cut, its advancement into the block determined by its weight rather than the suspension ropes. Other ropes attached to the blade ends allowed the blade to be pulled through the cut as it swung back and forth with a stroke of about one meter.

The cutting medium was probably quartz sand. It is harder than any of the minerals in the basalt, and perfectly capable for the job. Either the cutting occurred under water and sand was poured over the blade or a water/sand slurry was continually fed to the cut. The latter procedure would allow better visibility of the work.

It is probable that the sawing was done in a fixtured setup. Otherwise it is doubtful that workmen could manually direct a large flat blade to both keep its angle of attack constant and prevent any lateral excursion of the cutting edge as it shaved a single blade-width of material from the block face, as was done on block A. The blade had to be guided by *bearings* that kept its cutting edge in precise alignment, bearings which would not wear too rapidly under the abrasive action of the slurry and which could be easily repositioned when they did wear. The incised blocks that are unflawed may have filled this need, not only for the trimmed basalt blocks, but for other of Khufu's works, including his granite sarcophagus.

Earlier it was noted that the blade angle-of-attack was altered several times on block A. Was this done by rotating the blade or the block? As it would not be easy to change the operating plane of a fixtured drag saw, the only way these cuts could be produced by that device is if the block was turned. Considering what can be seen on these blocks, that explanation is easier to picture than the saw being held and guided by hand.

The Cutting Rate of the Saw

A reciprocating saw makes a scratch, or groove, on the cut face during each cutting stroke. Since the distance between the scratches here are about 1 millimeter, we can say that the saw traversed the material at two millimeters per cycle. As for the cycle time, or period, of the saw, if the saw swung from two-meter-long links then its action would have been akin to that of a pendulum, except for the drag caused by the cutting action and friction.[12] The period of a pendulum is approximately equal to $2\pi(L/g)^2$, where L is the length of pendulum arm (pivot to center of swinging mass) and g the acceleration of gravity ($9.8 m/sec^2$). With L as 2 meters the period would be 2.84 seconds. The maximum advancement rate of the saw would thus be a very respectable 2 mm/2.84 seconds, or about 42 millimeters per minute. It should be recognized, however, that the maximum advancement rate must correspond with the minimum resistance, i.e., width, hardness, of the material being cut.

Conclusions

If the procedure just hypothesized is accurate then the following can be concluded: 1) The invention of the swinging drag saw can be traced back more than two thousand years beyond its previous date. 2) The degree of mechanization indicated by this operation is somewhat more advanced than general views of the pyramid builders' technology level now hold. 3) The sawing done in this place represents a sophisticated operation of a mature industry.

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[12] To simplify, we will assume that the workmen exactly compensated for the drag effects by supplying the effort required to maintain true pendulum action. That way they could take best advantage of the blade's momentum.

Appendix

Excerpts from a letter of 19 June 1989 to the author by Dr. Robert Hamilton (cf. n. 4) concerning analysis of paving stones from Khufu's mortuary temple:

> The two samples of paving stones were examined by a combination of optical microscopy and x-ray diffraction. The two samples were very similar except as noted and are part of the same rock unit. A scientific description of the rock is:
>
> Pyroxene diabase—medium grained, hypidiomorphic-granular, sub-ophitic to intergranular. 65% plagioclase feldspar (labradorite in composition), 30% augite, 5% ilmenite. 5 to 30% of the intergranular material originally consisted of glass which has now been altered to a mixture of clays and iron oxides.
>
> The brown color is due to the chemical alteration of the volcanic glass which originally occurred between the grains. The glass has reacted with water and oxygen to form a mixture of iron oxides and clays. The browner of the two samples contains more altered glass than the blacker one.
>
> The alteration could be produced either soon after formation of the diabase or as a result of weathering near the surface over a long period of time. The alteration is a very slow process and was not produced after the quarrying of the rock. Despite their difference in color the two samples came from the same rock unit.