Building Cheops' Pyramid

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THE PYRAMIDS OF EGYPT, one of the Seven Wonders of the Ancient World, continue to awe and fascinate everyone who has stood in their enormous, timeless presence. Confronting them, one question is inevitably: "How were they built?"[1] The answer is not as constructionally simple as their geometrically stark shape. Professional Egyptologists and engineers alike have wrestled with this problem off and on since the 18th century without coming up with definitive or even generally accepted solutions. Investigation and speculation continue, with a new theory proposed every few years to explain how the thousands upon thousands of blocks were raised to their destined positions in the artificial mountain of stone.

Before evaluating any previously proposed solutions, or presenting new considerations of construction methods, it is necessary to review and comment on the traditional operations of the ancient builders and what is known about their equipment, tools, and customary procedures.

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It can be stated categorically that, except for a very few stones of relatively small size (and even these, only in special circumstances), the ancient Egyptians never lifted blocks by means of tackle and pulleys, nor suspended them by ropes from above.[2] Their massive, sometimes colossal monoliths precluded the possibility of suspending their dead weight from ropes. Instead, blocks of stone were raised—whether by wedge or lever or rocker—by jacking operations. Any jack is a device for exerting great pressure in moving an object (as in raising it) within a short interval of space. Its advantages are not only the great pressure it can apply but, above all, the precision of control over the application of that pressure, largely because it is exerted within such limited and prescribed boundaries.

For example, the water-soaked wedges used to sever an obelisk from the parent rock acted like jacks, in that they created even, gradually applied but intense pressure, yet only within the very small bounds of their own expansion: obviously, none of the force remained in effect once the rock had been split off along the line of the wedges. Similarly, levers used for raising blocks produce action analogous to that of jacks, in that great pressure is exerted when fulcrums are placed close to the block. Each lever arm may be long and counterbalanced with a rock for additional weight at its outer end. Action is confined within prescribed limits determined by the arc of the lever arm's sweep from the tilt-up "ready" position to the point where the arm is forced all the way down to the ground. No further action is possible until the block is secured and the levering action ready to be repeated.

Not all levers were used in a horizontal position—that is, for lifting; some were used in a vertical position—that is, for moving a block laterally. Levers were often used, too, for tilting, as in the rocker device.[3] The rocker (for raising medium-sized blocks of a few tons in weight) was a strongly built assemblage of wooden pieces consisting of two runners

1. Much has been written on Egyptian constructional practices, but most writers have either ignored significant problems or glossed over the details, and therefore proposed misleading solutions to the difficulties the ancient builders met and overcame.

This attempt to explain some of the considerations that have heretofore been passed over is an adaptation of part of the section on Egyptian architecture that will be discussed in my forthcoming book on the history of building construction.

2. With respect to the Egyptians' possible use of tackle and pulleys, Clarke and Engelbach, *Ancient Egyptian Masonry*, London, 1930, state unequivocally that no pulleys were used in the rigging of Egyptian ships. In Chapter IV, "Transport Barges," these authors assert (page 44) that "at the only place where a pulley would be expected none exist . . . ," and that "although hundreds of models and pictures of sailing boats are known, a pulley occurs in none of them, at any rate in dynastic times, and the evidence brought forward suggests that pulleys were unknown. Further, if they had been used, in building, for lifting the blocks of stone, it would be expected that a model pulley would have been found . . . yet none is found."

If no pulleys were used in connection with the relatively light requirements of sailing vessels, it is inconceivable that they would have been used for lifting heavy stones. In any case, pulleys appear to be entirely foreign to the constructional practices of the ancient Egyptians.

3. A. Choisy, *L'Art de bâtir chez les Égyptiens*, Paris, 1904, 80f., with numerous drawings, contains much about rockers and their operation ("Montage par l'ascenseur oscillant") though not all of this distinguished engineer's theories and suppositions regarding them should be accepted. For example, it seems most unlikely that the rockers were ever rotated about a vertical peg as indicated in figure 69, page 84, or that the ends of the rockers' runners were ever fashioned to such thin and sharp points as his drawings indicate.

(flat above and curved to a large radius below) that were linked by a number of stout rods in a pattern which allowed wooden levers to be inserted between two of them at either end in order to rock the device and its load, first one way then the other. As the device was rocked back and forth, slabs of wood (the shims) were positioned under the raised runners alternately to left and right; and in this way a practiced team could raise blocks quickly and with the minimum of danger to any of the work—or the workmen—below them.

Due to the great weight and massiveness of the stones they quarried, transported, and set up in their tombs and temples, it seems axiomatic that the Egyptians were restricted to raising blocks of stone—at least all but quite small ones—by one or another of the jacking operations described above. With the means at their disposal, it would have been impossible to lift colossal stones by tackle from above: the blocks were much too huge and heavy for such handling. In general, then, the process of elevating big, ponderous blocks of stone must have been a jacking operation from *below* rather than a lifting operation from above.

Parts of this process may have employed a constructional device that is occasionally used in Egypt today, the balance beam. Although no examples of it have been recovered from ancient times, its simplicity and purpose suggest that it was utilized by the ancient Egyptian builders. The fact that no example has survived from dynastic times can be accounted for partly by its cumbersome three-dimensional bulk, but more particularly by the likelihood that it has been in continuous use from ancient times to the present, so that each served to a point beyond repair and thereupon was discarded for firewood, leaving no trace as an individual entity, but surviving in generations of duplicates.

The balance beam is a device that works on the principle of the steel-yard.[4] It involves a raised horizontal beam free to rock on a fulcrum set beneath the beam near one end of it. By loading the end of the long arm of the beam with rocks, the short arm is given great mechanical advantage to lift within a limited distance. One or more of these balance beams may have been employed to suspend some of the less ponderous stones (such as the core blocks of the pyramids, for example) a sufficient amount to permit the insertion of a sled or runners beneath them. This is an example of the use of ropes to lift blocks momentarily, albeit not colossal ones. But it is essentially a jacking operation, acting within quite small limits and subject to close control throughout.

With sufficiently numerous and sufficiently long strong levers (counterbalanced at their outer ends if need be by one or more stones, once the inner end of each lever had been inserted under the block and the fulcrum firmly positioned) the Egyptians could jack up their largest monoliths as well. This process was essential in the case of raising colossal statues in order to permit heavy timberwork sleds to be slid under them preparatory to overland transit.[5] Doubtless a number of bosses were left protruding at either side of a huge stone statue for the levers to act against. Perhaps due to their temporary nature, and because the Egyptians would have regarded such bosses as distractions from the conceptual reality of the statue, they are never indicated in the contemporary representations.[6] They would have been necessary from a practical standpoint, nonetheless, to allow enough clearance for the sled to be hauled lengthwise between the two rows of levers and positioned under the block; conversely, upon arrival at the destined site, the sled would have had to be removed from beneath the statue by a reversal of this process, or some similar one. The projecting bosses, along with any other temporary utilitarian features utilized during the course of erection—like the timber sleds—would have been eliminated and/or discarded after they had served their practical purpose, and the finished surfaces came to be smoothed and polished.

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Invariably, the pictorial reconstructions that depict modern suppositions as to how the pyramids of Egypt were built show them under construction at a stage where they have

4. Engineer Olaf Tellefsen, *Natural History*, LXXIX, November 1970, 10f., presents drawings and comments on the use of the balance beam—he calls it the "weight arm"—which he admits (page 16) "has been the workhorse of peoples ever since man learned to build with heavy stones." He states (page 12) that the apparatus lifts a big stone "about a foot," enough to have "planks, rollers, and a pair of runners under it." So far, so good. But most of the operations and applications the author goes on to claim for this device are either patently impracticable (like his double weight arm [page 18] for both raising a block and moving it laterally in one operation), or unresolved with respect to problems of construction his theories cannot encompass (such as how the capstone of the pyramid was raised and installed in place).

5. Modern representations of ancient timber sleds are based upon mural relief carvings, particularly those showing the transport of a colossal statue of Djehutyhotep of the 12th Dynasty at El Bersheh in Egypt (often described and frequently illustrated), and gigantic winged bulls for the palace of Sennacherib at Nineveh during his reign which began in 705 B.C. (discovered by Layard and described and pictured, *inter alia*, by Theopheles G. Pinches, "Assur and Nineveh," *Records of the Past*, XII, 1913, 23–41).

A timber sled having 14-foot-long runners with four stout cross-pieces mortise-and-tenoned to the runners, and with many notches and sinkages to accommodate secondary pieces and attachments, is shown in clear detail in a scale drawing in Clarke and Engelbach, *Egyptian Masonry*, 89, fig. 85.

6. Erectional bosses left on column drums as well as stylobate and wall stones (to accommodate lifting slings) are familiar enough in Classical Greek construction. That they were used by the ancient Egyptians (to receive the lifting points of levers) is substantiated by the survival of unremoved projections on the casing blocks of the Third Pyramid at Giza and on the temples of the Theban area. See R. Engelbach, Chief Inspector of Antiquities, Upper Egypt, *The Problem of the Obelisks*, New York, 1923, 56, with photographic illustration.

achieved no more than a third or less of their final height. This is perhaps to be expected, since it is near the maximum level reached by the long paved ramp from landing stage at the riverbank; from there teams of laborers dragged the blocks three-quarters of a mile up to the building site. Parts of this massive ramp for the Great Pyramid at Giza are still traceable.[7] Moreover, a few writers claim that, in addition to this supply road, ramps were utilized at the pyramid itself by which all of its blocks were hauled on sleds up an ever-lengthening slope to their places at successive levels, all the way to the apex.[8] However, most serious writers agree that ramps would not have been constructed to the higher portions of this pyramid. So, beyond occasional speculations that are either vague or patently improbable, little if any attention has been focused on the problem of how the upper portions were built.[9]

On two counts, the access ramp was essential up to the level to which it was carried. One reason: to handle the constant traffic involved in supplying the enormous numbers of blocks used in both the core and the casing of the pyramid up to this stage of the work. The other reason: to facilitate the transport and maneuvering of the oversized blocks involved in connection with the King's Chamber, including the 50-ton granite plug at its entrance, the tiers of great ceiling beams, and the pairs of tilted relieving stones above them.

From this stage on up, the diminishing mass of the pyramid required many fewer stones, all but one of which were of a size that permitted them to be rocked up, in stepped sequences, from a staging area at the top of the wide access ramp. The one exception was the massive pyramidal capstone; and this, as we will see, could have been levered up vertically in regular stages, course by course, as each successive level was achieved, to its final position at the apex.

In order to get the normal-sized stones—both core and casing blocks—above the staging area at the top of the access ramp, rockers could have been used, such as the one discovered in a foundation deposit at Queen Hatshepsut's temple at Deir el-Bahari.[10] Using this simple device, a team

7. Clarke and Engelbach, *Egyptian Masonry*, 92, comment in considerable detail on construction ramps utilized in Egyptian temple building, particularly in the case of the pylon towers, but their book has little to say about other construction ramps. However, notices of extensive ramps—from quarry to river, and from river to pyramid—are given in Engelbach, *Obelisks*, 70, including fig. 26 (for ramps at Aswan), and in Karl Baedeker, *Egypt: A Handbook for Travellers*, 4th rev. ed., Leipzig, 1898, 121 (for the Third Pyramid at Giza). On page 109, Baedeker also quotes Herodotus's figures concerning the construction ramp for the Great Pyramid at Giza: "They first made the road for the transport of the stones from the Nile to the Libyan Mountains; the length of the road amounts to five stadia (1017 yds.), its breadth is ten fathoms (60 ft.), and its height, at the highest places, is eight fathoms (48 ft.), and it is constructed entirely of smoothed stone with figures engraved on it. Ten years were thus consumed in making this road and the subterranean chambers. . . ." Baedeker remarks that this route is still traceable, and indicates it on his map (between 132 and 133) as approaching the east face of the pyramid at an angle. When the Arabs removed the casing blocks to Cairo in the Middle Ages, they partially restored this ramp.

8. The distinguished Egyptologist I. E. S. Edwards, *The Pyramids of Egypt*, Harmondsworth, England, [1947] 1972, acknowledging (page 270) that "it must be admitted that Pyramid construction is a subject on which the last word has certainly not yet been written," asserts that "only one method of raising heavy weights was open to the ancient Egyptians, namely by means of ramps composed of brick and earth which sloped upwards from the level of the ground to whatever height was desired." Edwards devotes a number of pages (269–283) to describing "foothold embankments" and "supply ramps" which, he says (page 276), "would be raised to [each] new level of the Pyramid" as the work progressed; ". . . so the building continued to grow course by course until lastly the capstone . . . would be placed on the apex. . . . It may therefore be deduced that the capstone, already shaped but still in the rough, was taken to the top of the Pyramid on its sledge. . . ."

The amount of work and of materials involved in providing embankments and a supply ramp to the top of a 480-foot-high structure—all to be subsequently discarded and removed—staggers the imagination. Surely the Egyptians must have had a less prodigal means of utilizing both manpower and materials on falsework constructions of such vast extent, than to squander them on these enormous transient earthworks.

Furthermore, at least the long, long supply ramp would have served most inefficiently. For, in order to maintain the proper gradient, the ramp would have had to be constantly lengthened, its height augmented, and a smooth pavement of stones laid down at each new increment of height. How could all these interferences be going on while the constant traffic of hauling up the blocks was taking place?

9. Egyptologists generally have no training or experience—or even interest, judging by their scholarly output—in the matters discussed in this paper. Apparently it was ever thus. Here is what Engelbach wrote more than a half-century ago in *The Problem of the Obelisks*, 22: "There is quite a considerable literature on the subject, mostly done either by engineers (on a brief visit) with no knowledge of archaeology to enable them to control their assertions, or by archaeologists to whom engineering is a sealed mystery. While the publication of a new grammatical form or historical point will evoke a perfect frenzy of contradiction in the little world of Egyptology, the most absurd statements on a mechanical problem will be left unquestioned, and, what is worse, accepted. In most branches of modern archaeology the alleged savant must work in conjunction with the specialist, and the specialist needed for the subject under discussion is the foreman quarryman. This was brought home to me with great force when I was at work on the obelisk, and I shall never forget the ease nor the contempt with which an old Italian quarryman disproved some of my then most cherished theories. His range of knowledge may have been limited, but it was painfully accurate." A case in point is the unmistakably non-Egyptian procedure advocated by a modern engineer which was published in the *Journal of the American Institute of Architects*, LVI, August 1971, 50, claiming that the stones of the Great Pyramid were raised to their positions at successive levels on large counterbalanced elevator platforms.

10. This rocker is shown photographically as figure 89 opposite page 93 in Clarke and Engelbach, *Egyptian Masonry*.

To be sure, this rocker and a few others like it date from the New Kingdom, some 1100 years after the Great Pyramid was built. But we are extremely fortunate in having even these few authentic examples of a constructional device, whatever may be their ancient dynastic date. For although the Egyptians preserved in their tombs and foundation deposits countless examples of household objects and artifacts of all sorts (either as the objects themselves or as models of them, or in murals depicting their use), no of perhaps as few as four men—one working a lever to the right and one to the left, plus a couple of men to hand up and insert the shims—could raise a relatively heavy stone surprisingly quickly, skew it around on arrival at each stepped stage, and repeat the process from each new higher level. A central strip up the pyramid's slope above the access ramp would have had its casing blocks shaped rectangularly as steps, to be hewn off subsequently to a sloping plane when they were no longer required for construction.[11] In any event, a more detailed description needs to be given of the rocker device as it might have been used on the Great Pyramid.

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If the rocker device was indeed employed to raise blocks to the higher levels of this pyramid, a central zone of casing stones, where these operations would take place, would have to be formed as a series of steps instead of as the continuous sloping plane it would eventually become. But due to the steepness of the slope of the pyramid faces (some 51° 52′), each single row of casing stones, cut rectangularly as a step, would not have been deep enough to accommodate the process of raising stones by means of the rocker device. The bases of the casing blocks—and particularly the corner blocks—were substantially wider than the single step's tread; in addition, the width of this tread would not have furnished room enough to permit a 90° horizontal rotation of one of these blocks, as each lift was made, in order to shift it inward and start the operation of the next lift. Therefore a central stairway of two-course steps flanked by stairways of one-course steps would be necessary to raise blocks by the rocker device. These one-course steps would provide stairs by which the labor force climbed to and from the level at which the work was progressing, together with whatever gear, including ropes, timber blocking, levers, pry-bars, and other tools, they required for their tasks (Fig. 1).

That these lifts by means of rockers could be executed

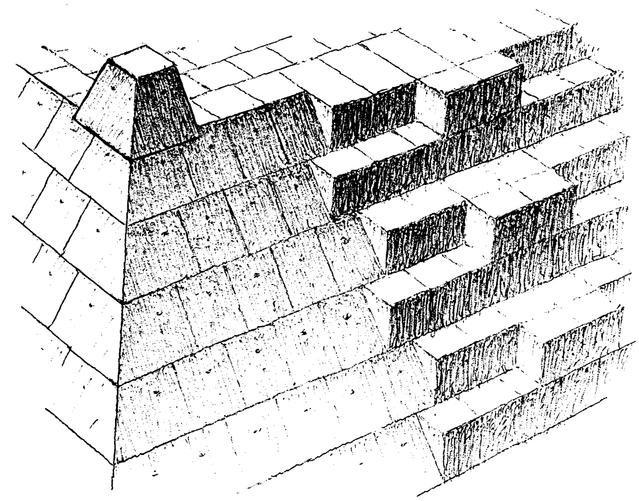

Fig. 1. To raise the blocks—both core and casing stones—up the face of the pyramid by the rocker device, a central stairway would have been needed. This would have been formed of casing blocks hewn rectangularly, later to be reduced to a smooth slope. Because of the steepness of the pyramid's slope, the two-course risers would be necessary to furnish room enough to maneuver the blocks at each lift where they had to be shifted inward.

with surprising rapidity can be suggested by recalling a clown act in the circus a generation or two ago. In it, a clown sat in a rocking chair, rocking vigorously back and forth while his companions inserted shims front and back. A height of eight or ten feet was achieved in a few moments and then, with no break in the continuity of his rocking, the clown returned to ground level in an equally short time as his companions removed the shims in reverse sequence.

In the ancient Egyptian operation, a skilled team of two men, each working a lever to right and left among the stout rods that linked the runners of the rocker, could utilize the weight of the block itself to reduce substantially the amount of effort they had to expend in the process of tilting the block, one way then the other. And other adept members of the team could position the shims in the proper place and at the proper instant, and secure them there as the alternate tilting of the block progressed.

The actual installation of the shims, and the pattern in which they were placed, are not self-evident for two reasons: (1) the height to which the column of shims had to be carried, and (2) the necessity to maintain stability and steadiness in the column as successive layers of it were added.

First of all, there had to be internal stability in the column itself (Fig. 2). This could be achieved by overlapping the shims in alternate layers. A length of rope zigzagged back and forth from each projecting end-piece would hold the shims secure against creep or shucking about laterally (since they were merely laid upon the previous layer without positive attachment as the column rose). Two or three turns

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utensils employed in building construction other than hand tools were preserved.

Except for brick-laying, conspicuously lacking are any murals which clearly illustrate the actual practices of building erection. For example, what was undoubtedly the most difficult and exacting engineering feat the Egyptians accomplished was that of erecting to an upright position monolithic granite obelisks that were nearly 100 feet tall. Yet no murals of this stupendous operation have ever been found.

It seems reasonable to assume that, in tradition-dominated Egypt, any device as simple as a rocker must have been in use with little if any change for millennia.

11. In this connection Clarke and Engelbach, *Egyptian Masonry*, 128, report that "In the Great Pyramid, as possibly in certain others, a large depression in the packing blocks runs down the middle of each face, implying a line of extra thick facing there. . . ." But whether this was done as a feature of the original construction or in connection with the stripping of the casing blocks by the Arabs in the Middle Ages is not clear.

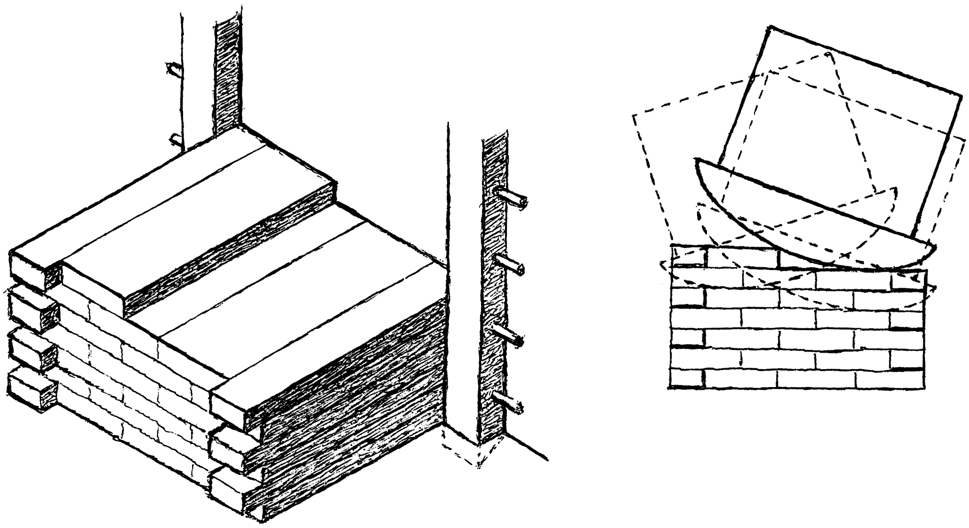

Fig. 2. Wooden standards (left), fixed to a double-course riser, bracket a column of shims whose narrower, longer end-pieces, alternately right and left, prevent the shims from spreading by being laced together with zigzagging cords (not shown) wrapped around their projections. The same or other cords looped around pegs in the standards would hold the column steady against the masonry. At right, a frontal view of the column of shims shows a loaded rocker in three successive positions.

around each of the projections, right and left, as these end-pieces came to be set in place would have consolidated the intervening shims at successive levels as the pile rose. Such a quick and simple linkage could be done without making the subsequent dismantling of the column a tedious or time-consuming chore.

Securing the entire column against tilting away from the masonry behind it, as well as preventing it from swaying laterally, might have been handled as follows. Two sturdy timber standards would be fixed securely to the face of the masonry riser so as to bracket the column of shims. Layer by layer, the shims would have been inserted between these standards with their far ends thrust against the masonry riser. The column of shims would be prevented from tilting away from the masonry by having ropes at intervals passed back and forth out around the pile of shims from pegs let into the far side of each standard.

These expedients would have provided for the security of a column of shims higher than any required in raising stones in stepped sequences of two-course lifts by the rocker device. In addition, this scheme utilized the minimum number of different elements in a simple alternating sequence, hence least subject to error in assembling it. The men who handled the shims did so from the front and consequently were at all times out of the way of the men at either side, who activated the levers. Once the boundary standards were secured in their upright positions, all the other operations involved in rocking up the stone blocks could be performed quickly and without waste motion or duplication of action. And this was true for both building up a column of shims and dismantling it preparatory to elevating another block. All the required paraphernalia were reusable again and again, with no undue strain or abrasion on any of it. Moreover, as the shims of a just-completed column were taken down, one by one, they could be inserted, one by one, into a column being erected at the next higher level.[12]

At least for the casing blocks, each lift probably involved somewhat more height in the column of shims than that of the riser of a two-course step. This was because the block had to be moved inward from the pile of wooden shims to the stone platform of the next step, where the ensuing lift would take place. Arriving at the top of a lift (somewhat over two courses in height), the casing block would have needed to be skewed around by the levers at right angles to its rocking position, and then tilted inward so as to be levered down onto a different rocker at the level of the upper step. To accomplish the operation of transferring a casing block from one rocker to the other, one pair of levers would be thrust through the rods of *both* rockers so as to keep their sloped tops in perfect slanted alignment, while the other pair of levers was used to ease the block down the slope from one rocker to the other (Fig. 3). From there, with the second rocker now loaded with the block, and skewed around 90° to its rocking position, the lift operation would be repeated at this next higher level.[13]

12. As is so often the case in mechanical processes, the description and explanation of the various operations outlined above take considerably more time—and make the procedures seem much more complicated—than would be the operations in practice.

13. It should be acknowledged that Clarke and Engelbach, *Egyptian Masonry*, 121, declare that the case against the Egyptians ever having used the rocker device to raise the stones of the Great Pyramid is "proved" by the negative evidence of the unfinished casing blocks of the Third Pyramid (which are not, they say, in the form of "a series of steps"), and by "all other known examples of unfinished masonry." Yet these thorough and reasonable writers admit (page 128) that the limestone casing of the Third Pyramid "is now broken up" so it would appear that more positive evidence should be sought for dismissing the use of the rocker. Clarke and Engelbach conclude (page 129) that "the foregoing notes on pyramid construction are not to be regarded as a complete and final exposition of the many problems hitherto unexplained, but rather as preliminary deductions which seem to

It seems likely that the men of each rocker team were responsible for, and performed their tasks at, a single lift operation instead of following a given block all the way up from ramp-top to where the block was to be set permanently in place.[14] Such an organization of man-power, with a different team at each step, would undoubtedly have been more efficient and saved time. Moreover, it would seem to have been consistent with the Egyptian deployment and utilization of a labor force at specific tasks and in prescribed areas of activity.[15]

follow from the information at present available, and which may have to be considerably modified in the light of future research."

Part of the reluctance to accept the rocker device may be due to the exaggerated claims which some have made for it, and the rather sketchy idea of its operation as given by some writers. For example, even W. M. F. Petrie, *The Arts and Crafts of Ancient Egypt*, London, 1909, 75, who had been probably the first to suggest its use, mentions shims that are wedge-shaped in section for the rocker's runners to ride up on, to right and left. These tapered shims are not only not necessary in the operation but, if used, would have considerably complicated the work of the men who inserted them. For, besides slowing down the procedure, they would have required a much greater expenditure of effort on the part of the lever-men in rocking the stone and holding it in the tilted position on either hand, until the next layer of shims could be shoved into position.

14. Baedeker, *Egypt*, 134, gives an English translation of the account by Herodotus (the earliest writer on the subject) of the construction of the Great Pyramid. Here is the portion of that account which pertains to the raising of stones in stepped sequence by means of small "machines" which may have been rockers: "This pyramid was first built in the form of a flight of steps. After the workmen had completed the pyramid in this form, they raised the other stones (used for the casing) by means of machines, made of short beams, from the ground to the first tier of steps; and after the stone was placed there it was raised to the second tier by another machine; for there were as many machines as there were tiers of steps; or perhaps there was but one machine, easily moved, that was raised from one tier to the other, as it was required for lifting the stones." (A somewhat differently worded translation is given in Clarke and Engelbach, 120f.) It is understandable that Herodotus's account of the Great Pyramid's erection seems somewhat garbled, contradictory, and questionable with respect to some of its supposed facts; for at the time the Greek historian got his information from the local guides, the Great Pyramid was already many, many centuries old. In any case, the procedures discussed above are consistent with either of the alternatives put forward in Herodotus's account.

15. Accustomed as they were to vast building projects which required the utilization of thousands of workers, those who were in charge of these undertakings were exceptionally skilled in the efficient organization and administration of the work force. This ability to organize and deploy great numbers of workers was, in fact, one of the most remarkable achievements of the Egyptian builders. For it involved such disparate logistical problems as the general one of housing and victualing very large numbers of workmen at the quarries and at the building sites, on the one hand, and, on the other hand, of detailed arrangements such as allotting a specific amount of space (some 22" x 22") to each of the quarrymen stone-cutters charged with freeing a granite obelisk from the parent rock of a quarry located more than 200 miles from the temple in front of which the obelisk was to be erected. For these and other instances of administrative efficiency in building operations see, for example, Engelbach, *Obelisks*, 43f.; James Henry Breasted, *A History of Egypt*, New York, 1905, 414; and E. Baldwin Smith, *Egyptian Architecture as Cultural Expression*, New York, 1930, 236f. Clarke and Engelbach, *Egyptian Masonry*, 3, state: "We cannot help admitting that they were perhaps the best organizers of human labour the world has ever seen, and their method of carrying out a task always appears to be the most efficient and economical, in principle at any rate, when we take into account the appliances which they knew and the methods of transport at their disposal."

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A considerable amount of speculation has been published about the possibility that the casing blocks were installed as a veneer from the top down after the core mass had been constructed. There can be no doubt, however, that the casing blocks were put in place as the structure rose. More than that: they were undoubtedly the first stones to be positioned as each new level was attained. The confusion all started with a misreading of Herodotus's statement that the pyramids were "finished" from the top down. His proper use of the term was not constructional but technical, and meant arriving at a finished surface by removing all excess stock, along with smoothing and polishing the final surfaces. It is axiomatic and inevitable that such a process takes place from the top down, just as it is equally obvious and inevitable that the construction of an all-masonry structure proceeds from the bottom up.

The outer surface of the casing blocks (destined to become the smooth face of the pyramid) was unfinished at the time they were positioned, with two inches or so of extra stock left on the weather face as protection from damage, both in transit and during the final finishing of the pyramid's even, polished planes.[16] At each level, these casing blocks would have been set first, all around the periphery, in order that their accurate emplacement (with one exception, as we will see) might be handled from *within* the area of the working platform at each level. Thus each casing block could be positioned quickly but with great nicety by nudging it out to its destined site at the edge of the platform, using pry-bars or levers that found a purchase in one or another of the joints between the core blocks.

The procedure would have begun with the corner casing blocks, those double-sloped and largest of all the "regular" stones of the pyramid. These would be set temporarily farther out along the diagonal of the square platform than their subsequent final position. This provisional position would permit the casing blocks in each of the straight runs

16. It is not generally appreciated, nor has it been adequately acknowledged in print, how widespread throughout ancient times (and even in the medieval period) was the practice of quarrying stones oversized; that is, with extra stock left on the faces of stones that were to be subsequently dressed down to their finished surfaces. To be sure, most of the practices employed by Greeks during the Classical period are familiar, such as the oversized diameters of the column drums to protect them from injury in transit and during erection before the flutes were cut, and the bosses left on these same drums to accommodate the hoisting slings in setting them accurately in place. But the extent to which the Romans—and above all, the Egyptians—utilized oversized and/or projecting features has not been sufficiently reported or properly studied.

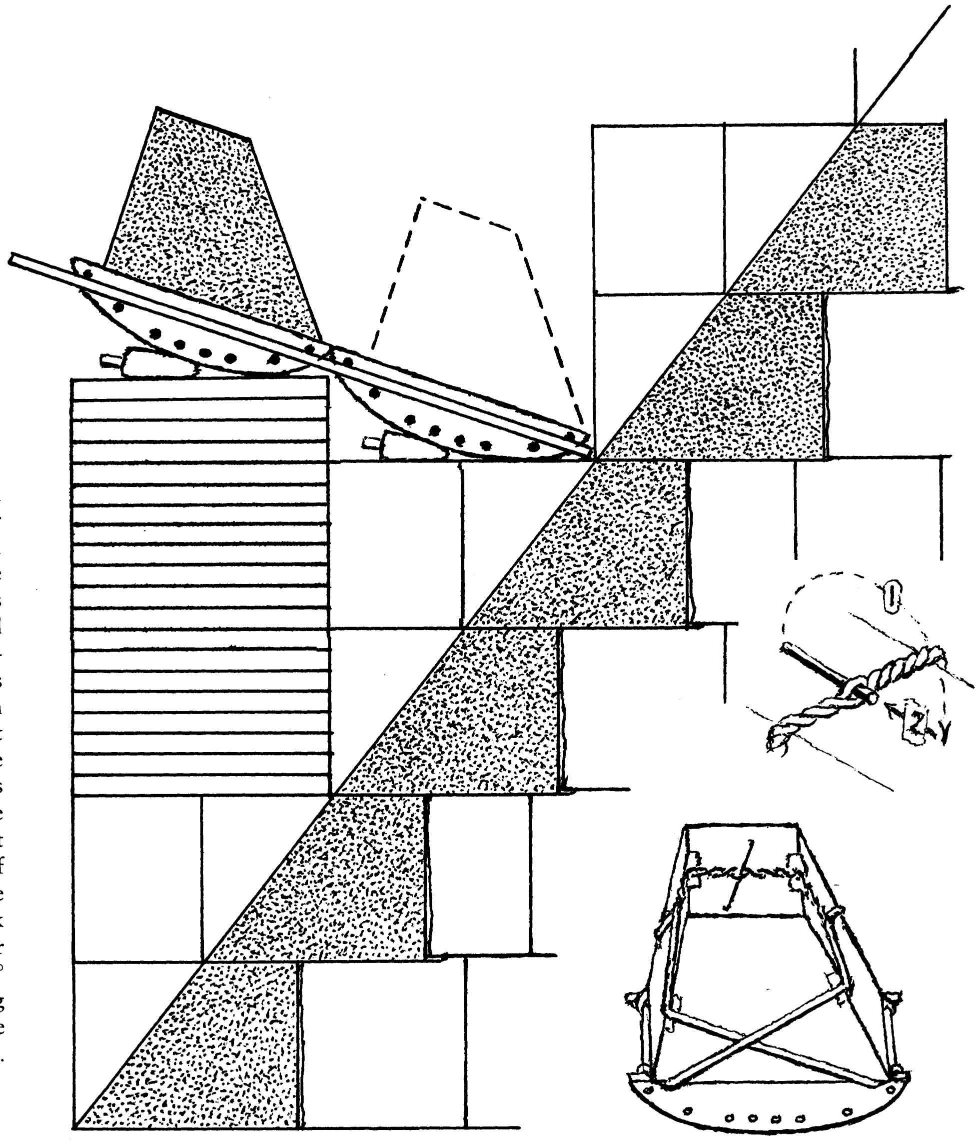

Fig. 3. In order to shift a block inward onto another rocker when the first rocker had reached the top of its lift on the column of shims, the two rockers would be aligned as shown and secured by handy wedges underneath the runners and by levers thrust between the rods of both rockers. This would have made it possible for the block to be skidded down the slope thus formed, in order to shift the stone from one lift position to the next higher one. The main portion of this drawing shows the extreme case of a corner casing block being shifted, which accounts for what would appear to be a 180° turn of the block from its rocking position, but is in reality the usual 90° turn.

along the sides of the platform to be positioned snugly against each other (such as those still to be seen in the extant masonry of the casing's lowest courses, where the joints are so hairline as to be scarcely noticeable).[17] When the four straight runs were in tight alignment, the corner casing blocks would be drawn inward diagonally to their final position. To accomplish this maneuver, ropes would be looped over the corner block around wooden plugs driven into and projecting from shallow holes that had previously been cut into the extra stock of this block's two outer faces.[18] Then, with the loop at the other end of the rope secured to a fixed anchorage among the core blocks, the rope strands would be twisted together around a heavy stick (as shown, for example, in some of the bas-reliefs of the transport of colossal monoliths, to tighten the ropes securing it to its sled). This simple device, known as a Spanish windlass, shortened the rope as it became more twisted, causing the block to inch inward in a controlled jacking action toward the fixed end of the rope (Fig. 4).

17. Clarke and Engelbach, *Egyptian Masonry*, figure 96 opposite page 98, note that the joints between the granite casing blocks that survive *in situ* at the base of the Great Pyramid in no place gap more than one fiftieth of an inch. Any practicing mason knows that it is impossible to set rectangular blocks of stone—even ones far smaller in their areas of contact than these—with such astonishing tightness by slipping any of them between others already in place. Hence it appears to be undeniable that the procedure followed here was to juxtapose the big casing blocks to right and left, beginning with a block at or near the middle of each course, with the corner blocks acting as terminal closures by being drawn diagonally inward against the completed runs on two adjacent faces of the pyramid.

18. A shallow hole in the excess stock, with wooden plug inserted, is shown in figure 21 at C, of A. Choisy, *Histoire de l'architecture*, 2 vols., Paris, 1929, I, 34. The author asserts that auger holes can be found in the stones of the Great Pyramid, where, in all probability, these plugs were implanted, although he does not identify which stones or which of their faces possess these holes.

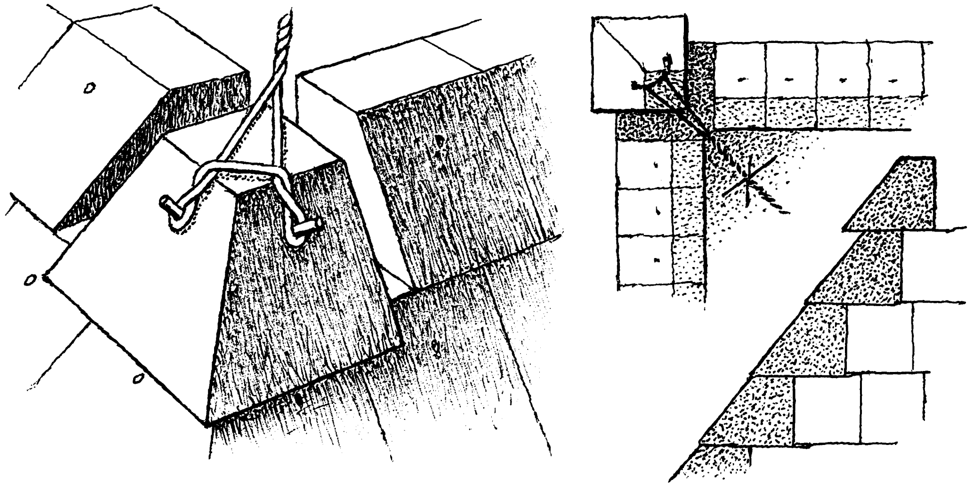

Fig. 4. The corner casing blocks would have been placed first, at a given level, out from their intended position, but in line with one or another of the pyramid's diagonals. Only by means of this temporary offset position could room be given to maneuver the stones of the straight runs of casing blocks into tight juxtaposition. The Spanish windlass device—to shorten the rope by twisting it—thereupon drew the corner blocks diagonally inward to a snug fit.

There was another practical reason for this procedure. This was to align the salient sloping edge of each corner block, accurately according to sight-lines established from below for the diagonals of the pyramid, to forestall any twisting in these edges. Each of the four faces of the Great Pyramid represented, when completed, an area of approximately five acres; and it was important that the intersection of each pair of these sloping surfaces be absolutely straight, without any twist. Hence the accurate alignment of the corner casing blocks along the diagonal was a first priority and one which, having been painstakingly ascertained at the start of each new level of the construction, was undeviatingly maintained in the final positioning of the corner blocks by the Spanish windlass device.[19]

The exception referred to above in positioning the casing blocks was the break that occurred at the middle of the access side. For here it would have been most inconvenient and troublesome, if not impossible, to move all the core blocks up over the rim of the casing blocks and to lower them into snug alignment within the established confines of this outer cordon of stones. What was probably done was to leave a breach in this outer cordon, perhaps three or four blocks in width. The core stones would be maneuvered through the breach to their destined compact juxtapositions, directly from the top of the access stairway. The jambs of this embrasure would have been slightly splayed, that is, a bit wider apart on the outside than on the inside.[20] When all the core blocks were positioned and it came time to fill the embrasure with the three or four remaining casing blocks, these could be eased into place from without (somewhat like inserting the keystone of an arch, as it were). These casing blocks could be maneuvered from the outside, due to the shelf or ledge provided at that spot in connection with the operations of raising the blocks—all of them, in fact—to this level of the work. And the blocks that finally closed the breach themselves became part of the stairway used to get both the core and casing stones for subsequent courses up to higher levels of the pyramid. Since these casing blocks which closed the breach did not have sloping faces but were rectangular in section, they could be nudged inward by pry-bars without damage to their outer lower edges.

In the tight and careful placement of the many thousands of blocks in this enormous structure, the nature and the function of the mortar used in the Great Pyramid is important. It consisted of sand and gypsum (rather than lime) with a considerable admixture of impurities. Consequently it had practically no adhesive power. None was needed, however, for friction and dead weight secured permanent stability for each of the ponderous blocks. The mortar, squeezed into extremely thin beds by the stones' weight, had two other functions. One was to insure that each stone rested evenly and completely on the blocks beneath it, with no voids or hollow areas that could cause cracks in the stonework because of uneven weight distribution. Its other function was to facilitate the laying of the stones.[21] Both were essential in the Great Pyramid's construction.

19. Maintaining accuracy of batter in the faces of the pyramid, and the avoidance of twist in the salient angles where a pair of these faces intersect, are matters that are dealt with in considerable detail by Clarke and Engelbach, *Egyptian Masonry*, 124–129.

20. Clarke and Engelbach, *Egyptian Masonry*, have a whole chapter (IX, with many photographic illustrations and scale drawings) on "Dressing and Laying the Blocks," in which vertical joints—though slightly oblique in plan: "Type A"—are documented and illustrated with respect to some of the casing stones of the Great Pyramid, and elsewhere.

21. Clarke and Engelbach, *Egyptian Masonry*, 78, put it this way: "It was the presence of the mortar in the bedding joints which enabled the blocks to be laid. Without it, the Egyptians could not have laid them at all. . . . Mortar is made use of to form an even bed and to facilitate 'setting,' which is the technical term for getting a block exactly into place; the mortar being, practically speaking, a lubricant. It is obvious that, unless a stone of considerable weight is laid on a bed of such a nature, so that it can be adjusted hither and thither, good setting cannot be obtained. For masonry of any fineness, a layer of some sort must be used having the consistency of butter—in other words, a lime-cream, which as a cement is without value. . . ."

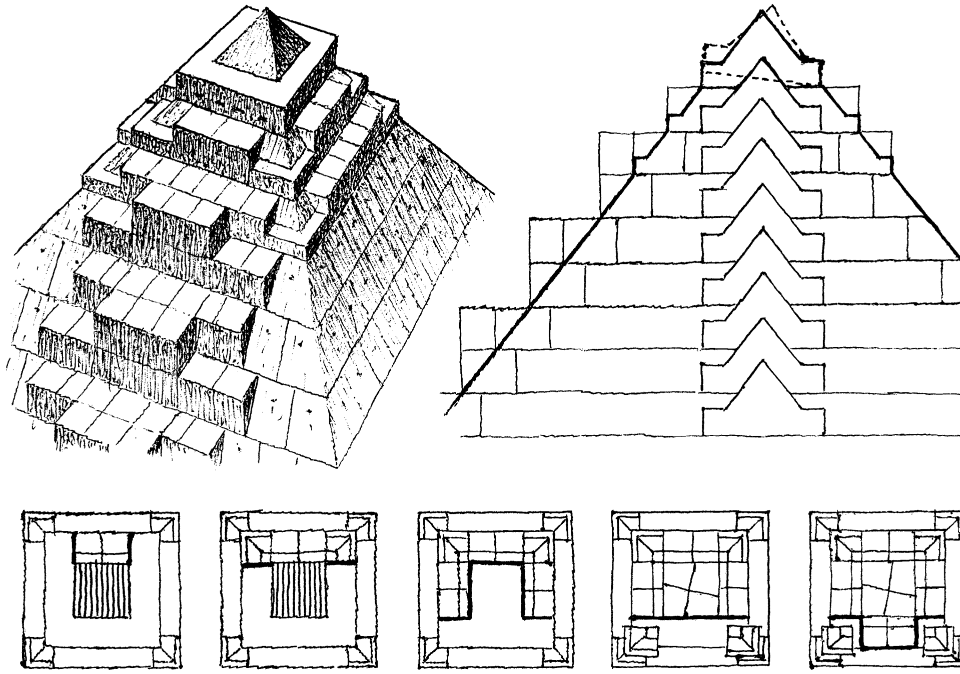

Fig. 5. Schematic diagram (right) of incremental lifts of the capstone block. Bird's-eye view (left) of top of pyramid, showing access stairway and constructional ledges at the two uppermost courses. Series of plan views (below) indicating the order of installation for all the blocks in the highest course, just below the capstone. Core blocks beneath the capstone would have had slightly skewed joints (exaggerated in the drawing) to permit their snug installation.

* * *

Meanwhile, the ponderous capstone would have been levered up, a course at a time, from its position in the center of one platform to that of the next, so that the core blocks could be consolidated beneath it. By tilting the capstone first in one direction, the timber blocking could be withdrawn from below its raised side and core blocks permanently inserted there; levering it in the opposite direction, the rest of the timber blocking could be replaced by core blocks. Then it would be raised to a new course level on timber blocking, and a similar operation repeated at that higher level.

The placing of the stones of the two highest courses of the pyramid was complicated by the presence of the massive capstone around and under which the "ordinary" blocks had to be maneuvered. Here, because of the interference of the temporary timber blocking, the stones of these uppermost courses had to be nudged into place from the outside instead of within the periphery of the structure. But by having all the casing stones in these uppermost courses (except the corner blocks) hewn not with sloping outer faces but rectangularly, horizontal ledges were produced all the way around, in order to provide additional space to fit the blocks of the next higher course around the capstone's blocking. It was from these ledges, too, that pry-bars could inch the blocks accurately into position from the outside inward, in substitution for the Spanish windlass device. Slots chiseled in the floor of these ledges, to act as purchase for the pry-bars, would of course disappear completely when the time came to hew the ledges off entirely and reduce the pyramid's stepped faces to their smooth slopes. In the meantime, however, the ledges furnished indispensable working space—a solid scaffolding, as it were—all the way round, to accommodate the operations of setting the uppermost stones in the crowded and constricted scene of operations at the top of the pyramid (Fig. 5).

Here, and particularly at the penultimate course immediately below the capstone, the order in which the blocks were delivered up the two-course steps of the supply stairway was especially critical. The first blocks to be positioned in the topmost course were the central casing stones on the far side from the stairway. They, and then the corner blocks flanking them, would have been maneuvered out around the blocking under the capstone and nudged into their destined location. Previously, the blocking would have been limited, in plan, to its minimum feasible area; that is to say, somewhat less than the space that would be left between opposite pairs of the casing blocks when they were all in final position. Next in order came the setting of the casing stones to right and left of the blocking, in accurate and closest alignment. With the casing blocks established on three sides, the temporary timberwork blocking could be removed, since the weight of the capstone could now be transferred to shims resting on these permanently positioned casing blocks. Then core blocks would be packed in solidly, filling the area that had just been occupied by the timber blocking. Next to be brought up were the two front corner blocks, which were temporarily positioned half a foot or so to right and left of their final positions, out of alignment with the casing blocks behind them. This temporary location allowed sufficient room to permit the front casing blocks—those at the top of the access stairway—to be set accurately in place, close against the core blocks behind them, after which the flanking corner blocks were eased into their destined permanent locations with the aid of pry-bars. Which left but one last positioning operation: that of lowering the capstone itself onto the completed stone platform furnished by the topmost course of blocks. This would have been accomplished by means of levers inserted into sinkages near the base of the capstone (or under bosses there), tilting up this terminal block sufficiently for the workmen to draw out the shims and ease the block down to its final resting-place as the apex crowning the gigantic stone mountain.

With core and casing blocks and capstone finally in place, the four faces of the pyramid needed to be stripped down to their intended smooth planes and polished. The stripping—technically known as "dressing"—would have involved removing the constructional steps, hewing off the capstone's bosses, and smoothing away the extra inches of stock left on the weather faces of all the casing blocks.

Scaffolding for the stripping operation could have been minimal and of the simplest kind, in spite of the enormous areas to be worked. Capitalizing on the protective extra stock with which the casing blocks were provided, holes would have been previously cut at intervals into this excess material, the axes of the holes being made normal to the slope of the pyramid's face. Into these holes short wooden rods would be driven at a given level to serve as supports for a narrow ledger or foot-rest from which the men charged with reducing the surface could work. As the blocks of one level were made smooth, eliminating all trace of the next higher row of holes, the rods would be driven into existing holes in the next lower tier, the foot-rests shifted to that level, and the stripping process repeated there. Meanwhile the detritus of rock chips and fragments would cascade down the slope to the base of the pyramid where it was collected and removed to a very extensive dump nearby, still extant today as an artificial plateau of discarded masonry scraps.[22]

* * *

This explanation of building practice cannot be thoroughly documented today. It even seems doubtful that we will ever know with certainty how this gigantic structure was actually brought into being, stone by stone. Here an updating of the thorough and comprehensive investigations presented in the pages of Clarke and Engelbach was proposed. The building problems of the ancient Egyptians were examined from the vantage point of the practical approach of the general contractor, keeping in mind what is known about Egyptian tools, methods, and principles of construction. Only by taking into account and pursuing the consequences of a particular scheme can the feasibility of that scheme be assessed.

To this end, the procedures discussed here may provide a fresh look at the difficulties encountered, along with the ramifying secondary problems that had to be dealt with. It may be that the rocker device was not in fact what the builders of the Great Pyramid employed. But here is an analysis of how it might have operated, had it indeed been used as the primary erectional technique. In any event, a comprehensive effort should be made to assess in realistic detail the complete picture involved in the erectional procedures of the ancient builders, whose operations have both fascinated and baffled travelers and professional engineers alike for centuries.

22. On page 318 Walter Woodburn Hyde, "A Visit to the Pyramids of Gizeh," *Records of the Past*, IX, 1910, 246–265, 312–327, with 15 illustrations, states that "vast quantities of chips—estimated at one half the bulk of the pyramid—were thrown over the cliff to the north and south of the 'Great Pyramid,' thus forming an artificial enlargement of the plateau, extending for some hundreds of yards outwards from the rock's edge. These masses of chips are very interesting; for they show peculiar stratification, according to the kinds of refuse thrown out at different times, strata composed of large chips alternating with those of smaller ones. . . ."

Of course, most of this accumulation would have already been built up from the extensive operations of the stone-cutters, both those who had excavated innumerable tombs in the bedrock around the pyramids, and those who had been charged with accurately shaping blocks at the site previous to their incorporation in the pyramid. But there would have been much additional debris as a result of the stripping process, particularly of the larger fragments Hyde mentions, which might have come from hewing off the steps of the access stairways.