Building the Great Pyramid: Probable Construction Methods Employed at Giza

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RESEARCH NOTE

Building the Great Pyramid

Probable Construction Methods Employed at Giza

JAMES FREDERICK EDWARDS

Every year, droves of visitors travel to Egypt to gaze upon the oldest survivor of the seven wonders of the ancient world. Most of them ask the same question: "How was it built?"

The largest in a group of three, the Great Pyramid was begun by King Khufu during the Fourth Dynasty of the Old Kingdom in Egypt, which commenced with the reign of King Sneferu, approximately 2613 B.C.E., and ended with the death of King Shepseskaf circa 2500 B.C.E.[1] Its original outer casing stone and some other blocks have been removed, but at 147.5 meters high and 230 meters square at the base, its volume, when first built, would have exceeded 2,600,000 cubic meters. It has been estimated that 2,300,000 separate blocks of stone, the majority weighing between 2 and 3 tonnes, were used in its construction.[2] There has always been much speculation about how it was constructed, and Egyptologists and historians are divided

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1. Of the numerous books written about Egyptian pyramids, a good general source is Mark Lehner, *The Complete Pyramids* (London, 1997). For Egyptian construction methods, see Dieter Arnold, *Building in Egypt: Pharaonic Stone Masonry* (New York and Oxford, 1991).

2. Lehner, 202. Most of the building stone used for the core blocks was quarried close by the pyramid. The stone for the outer casing blocks, which was a harder, more homogeneous white limestone, was brought from Tura, across the Nile Valley from Giza. The small number of large granite blocks used for the burial chamber, and for plugging up passages, were brought from Aswan, some 500 miles to the south.

about the building techniques employed. The majority favor the idea that gigantic ramps were used to lift the building blocks to their locations within the structure, while others claim that levering systems were employed.

The principal theory is that a massive ramp was built against one full face of the pyramid, and was lengthened as construction proceeded.[3] Various gradients have been proposed for such a ramp, although a slope of 1 in 10 is considered the most practical. Such a ramp would have been about 1 1/2 kilometers long and have required more than three times the volume of material used in the completed pyramid. Apart from the mammoth task of building it, maintaining the ramp during construction of the pyramid would have been a colossal undertaking in its own right. It is difficult to guess where such a ramp might have been located. A 1-in-10 gradient could not have been achieved from the adjacent quarry area, and the local topography and other building works in the vicinity would have placed severe restrictions upon its location.

Another proposal is that there was a spiral ramp or combination of ramps around the structure of the pyramid. Numerous virtually insurmountable problems would have been associated with physically supporting and constructing such ramps.[4] Furthermore, they would have afforded only a relatively narrow hauling surface, a problem exacerbated by the simultaneous use of the ramp by both the ascending and descending hauling teams. The hauling teams would also have encountered great difficulty negotiating the tight right-angled turns at each corner of the pyramid.

Although the foundations of a number of small, embankment-like structures have been discovered adjacent to the Great Pyramid, it seems likely that these were only used for elevating blocks at a very low level during the initial stages of the pyramid's construction.[5] Large ramps of any type would have generated an enormous amount of material, and there is no such volume of material at or near the construction site. There is, therefore, a dearth of conclusive archaeological evidence supporting the theory that such massive ramps were constructed in the vicinity of the Great Pyramid.

3. The various ramp theories are fully explained by Lehner, 215–17. See also Zahi Hawass, "The Pyramids," in *Ancient Egypt*, ed. David P. Silverman (London, 1997), 168–91; Arnold, 98–101.

4. Peter Hodges, *How the Pyramids Were Built*, ed. Julian Keable (Dorset, 1989), 125–27. As a spiral ramp progressively increased in height its sides would need to be vertical in order for it not to encroach upon its own lower stages. For such a structure to be inherently stable it would need to be constructed from material meeting criteria approaching those for the pyramid itself (i.e., stone). It is also extremely doubtful that support for such a structure could be provided off the angled faces of the pyramid.

5. Lehner, 217, 221. Shallow, low-level ramps were probably used during the construction of the lower courses of the pyramid. The exposed lower courses of outer casing blocks on the adjacent Menkaure pyramid reveal a number of undressed stones that were probably initially covered by such ramps.

Alternatively, it has been proposed that every individual block of stone used in the construction of the Great Pyramid was elevated into position using levers and packing pieces.[6] Such a technique involves jacking up a block at one side with lever and fulcrum, inserting a wooden packing piece, jacking up the opposite side of the block in a similar manner, and then repeating the process until the desired elevation is achieved. It has been estimated that a vertical distance equivalent to the thickness of one course of block in the Great Pyramid could have been achieved in about 5 minutes by a team of four men operating two levers per side.[7] The exposed core blocks of the Great Pyramid suggest that it was constructed as a "coursed" pyramid, as it consists of level courses of stones. Although these courses vary slightly in thickness, each separate course appears to be a level array of squared stones. Once a block had been lifted one course, it would have had to be moved horizontally onto the bottom of the next course, whereupon the procedure could be repeated, until the working plateau had been reached. By the time the Great Pyramid had reached half its completed height, some fifteen hundred separate jacking actions, together with approximately eighty horizontal transfers, would have had to be undertaken for a single block, all requiring a degree of precision in order to avoid any mishaps.

Both the ramp and lever methods would have been inefficient in their deployment of personnel, for in both cases the haulers and lifters would have had to ascend and descend the pyramid structure as part of each elevating cycle. Such approaches would also have been extremely time consuming; at the halfway point in the pyramid's construction the elevating cycle for one core block would have been forty minutes using a straight ramp and seven hours using levers.[8]

It has also been proposed that a type of shaduf—a counterbalanced sweep used in the ancient world to raise water—could have been used to lift the pyramids' building blocks.[9] Such an approach would have necessitated

6. Hodges, chap. 1. One must conclude from a perusal of this book that Hodges is constantly attempting to make his theories fit in with the writings of Herodotus, who visited the pyramids at Giza some two thousand years after their construction. Herodotus' writings are open to many interpretations, and because of the length of time that elapsed between the pyramids' construction and his visit, they can at best only be taken as conjecture. For the translated details, see *Herodotus: The Histories*, trans. Aubrey de Selincourt (Harmondsworth, 1954).

7. Hodges, 83.

8. At the halfway point in the pyramid's construction, assuming a hauling speed of 0.6 meters per second (1.36 miles per hour) the time taken to achieve a nonstop ascent of a 1-in-10 ramp would be about twenty-one minutes. Allowing time for descending and contingencies, the "hauling cycle" can be estimated at forty minutes per block. For the levering technique described by Hodges, the average time to elevate a single block at this same point in construction works out to about seven hours, although there would have been scope for elevating numerous blocks in unit time using this method.

9. Richard Koslow, "How the Egyptians Built the Pyramids," www.egyptspyramids.com/html/article.html.

the construction of substantial wooden towers in order to withstand the forces involved. It is proposed that the pyramids' outer building blocks were initially left square and untrimmed and that the wooden towers were moved up the stepped sides of the pyramid as construction proceeded—an operation fraught with danger, as well as an extremely time-consuming and impractical one.

Because of the problems alluded to, it must be concluded that these ramp and lever theories present unsatisfactory resolutions relating to the methodology employed for the elevation of the building blocks.

Hauling Stone Blocks

It is possible to deduce, from contemporary and even ancient evidence, certain scientific parameters relating to the hauling of stone blocks.

During recent experiments relating to the hauling of stone blocks at Karnak Temple, it was found that three men could pull a sledge-mounted block weighing one tonne over a stone surface that had been lubricated with water to reduce the effects of friction.[10] From this evidence we can, by making some practical assumptions, determine the frictional effects encountered by the haulers.

Friction is a resistive force that prevents two objects from sliding freely against each other. The relationship between the force of friction and the pressure between the two surfaces—called the normal pressure—is given by the coefficient of friction, which is generally denoted by the Greek letter μ. There are different types of and values for the coefficient of friction, depending on the type of resistive force. In the case of hauling stone blocks, we are interested in the kinetic coefficient of friction, which concerns the force restricting the movement of an object sliding on a relatively smooth hard surface.[11] This is represented by the equation $\mu = F \div N$, where F is the force of friction and N is the normal pressure between two surfaces.

At this stage we have to make an assumption regarding the individual force exerted by each hauler. It has been estimated that an individual man is capable of exerting a pulling force equal to 150 pounds, or 68 kilograms.[12] This would appear to be a credible number, as it seems reasonable to think that an adult male would be capable of exerting a force approaching his own body weight, and 68 kilograms would be 90 percent of the body

10. Lehner (n. 1 above), 224.

11. For examples of kinetic coefficients of friction for various mixes of materials, see www.physlink.com/Education/AskExperts/ae139.cfm. There appear to be no definitive data available relating to the value of kinetic coefficient of friction between wood and lubricated stone. The kinetic coefficient of friction between wood and wood (dry, smooth, and unlubricated) is 0.2. This value would diminish if a lubricant were introduced between the sliding surfaces.

12. Koslow, 2.

weight of a man weighing 75 kilograms (165 pounds). Substituting known and assumed values for the example of hauling carried out at Karnak yields this estimated kinetic coefficient of friction:

$$\mu = \frac{F}{N} = \frac{3 \times 68}{1 \times 1{,}000} = 0.204$$

We can now turn to an example of hauling known to have been carried out in ancient Egypt. In the Twelfth Dynasty tomb of the nobleman Djehuty-hotep at Deir el-Bersha, there is a wall painting (fig. 1) showing a statue of the tomb owner being hauled on a sledge. The statue, which is known to have weighed about 58 tonnes, is being hauled by 172 men in four files of 43. A man is shown standing on the base of the statue pouring liquid from a jar onto the ground in front of the statue/sledge assembly. Three other men are carrying yokes of two fresh jars of liquid each, while other men walk behind the statue. Three more men are carrying what appears to be a large lever.[13] We can use the estimated kinetic coefficient of friction determined for hauling the Karnak block, 0.204, to test whether the painting is accurate in terms of the number of haulers depicted in it. If the force of friction $F = 68 \times H$ (where H is the number of haulers) and normal pressure $N = 58$ tonnes, or 58,000 kilograms, then

$$0.204 = \frac{68 \times H}{58{,}000}$$

$$H = \frac{0.204 \times 58{,}000}{68} = \frac{11{,}832}{68} = 174$$

As the number of haulers depicted in the tomb painting is 172, the correlation between the two sets of data is remarkably close.

What conclusions can be drawn from these results? First, assuming that 68 kilos is a reasonable estimate for the equivalent force exerted by one hauler, then the estimated kinetic coefficient of friction for hauling both the Karnak blocks and the statue of Djehuty-hotep is 0.204. Second, while the estimated kinetic coefficient of friction would vary depending upon the exact amount of pulling force required to be exerted by the haulers, the important factor is that there is a direct correlation between the contemporary and ancient estimates, which implies that the amount of required pulling force exerted by each individual hauler was similar in both cases. Third, the calculations support the assumption that the wall painting in the tomb of Djehuty-hotep at Deir el-Bersha is accurate in terms of the number of haulers depicted in it. Fourth, the estimates and calculations provide

13. Lehner, 203.

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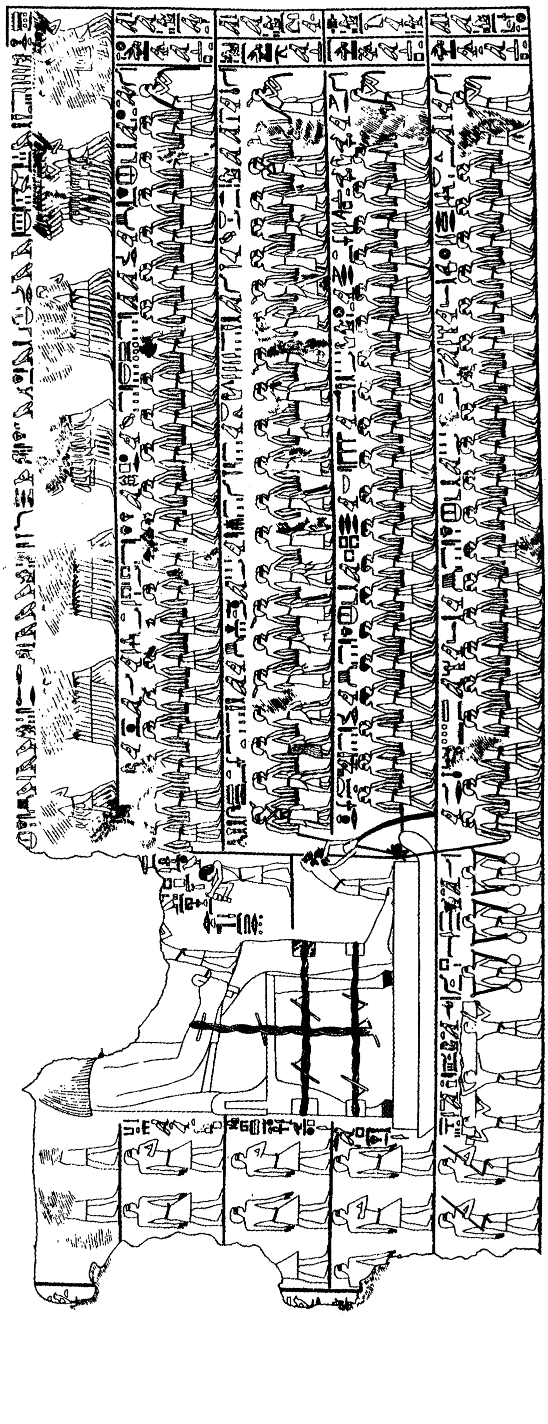

FIG. 1 The wall painting in the tomb of Djehuty-hotep showing his statue being moved by a team of men dragging it on a sledge. (Mark Lehner, *The Complete Pyramids* [London, 1997], 203. Drawing by Philip Winton. Reprinted with permission of Thames and Hudson, London and New York.)

strong evidence that the lubricating medium used for moving the ancient statue was water.[14]

Adequate ropes would have been required to haul the blocks of stone. A rope of about 8 centimeters diameter would have been a practical size for a team of haulers to handle. Such ropes are capable of hauling loads in excess of 4 tonnes and can be made from the doum palm, a tree indigenous to Upper Egypt.[15]

Lifting the Stone for the Great Pyramid

From an engineering point of view, a basic question to ask, when attempting to propose probable methods and techniques involved with lifting the building blocks is, "why build separate ramps when the pyramid has four inclined planes as an integral part of its structure?" Granted, these inclined planes are steep, lying at 52 degrees to the horizon. But we can examine the forces and methods required to lift blocks up them based on the aforementioned parameters coupled with some simple mathematics.

The force P to pull a body up an inclined plane (the force being parallel to the plane) is given by the equation $P = W(\mu\cos\alpha + \sin\alpha)$, where W is the weight of the body, μ is the kinetic coefficient of friction between the body and the plane, and α is the angle that the inclined plane makes with the horizon (fig. 2).[16] As the majority of the core blocks in the Great Pyramid weigh

14. Other practical experiments relating to the hauling of stone blocks have also been carried out; see Michael Barnes et al., *Secrets of Lost Empires* (London, 1996), 61–62. In 1995, a team of Egyptologists built, in Giza, a small pyramid using blocks similar in size to those used for the core and outer casing blocks of the Great Pyramid. When completed, this tiny pyramid was 6 meters high and 9 meters square at the base. The team moved 2-tonne blocks mounted on wooden sledges over a surface of *tafla* (a type of clay) and wood, lubricated with water, using two files of men hauling on 4-centimeter-diameter ropes. It was found that twelve men could move the blocks with ease up an inclined roadway. This team favored the idea that massive ramps had been constructed in order to lift the building blocks of the Great Pyramid, and they used ramps and lever techniques to construct their tiny version of a pyramid. In effect, they constructed the very last few blocks of the Great Pyramid, but at ground level—which, although a useful exercise in some respects, did not meaningfully relate to the massive scale of work carried out on the ancient monument.

15. *Machinery's Handbook*, 20th ed. (New York, 1978), 1122–26. The working load of an 8-centimeter fiber rope, when used at low speeds (up to 1.5 meters per second), is about 4.2 tonnes. The ultimate tensile strength of such a rope is about 29 tonnes, and it weighs approximately 4.3 kilograms per meter. The working load is calculated conservatively and provides a safety margin of almost 7 (29 ÷ 4.2). The ancient Egyptians would not have been aware of such criteria, and they probably subjected such ropes to a higher working load. Because of the high safety factor, some excess loading would have been acceptable as long as the rope was not subjected to a suddenly applied shock load. When hauling blocks of stone it is reasonable to assume that loads would be gradually applied and that motion would be within the upper limit of 1.5 meters per second.

16. Ibid., 307.

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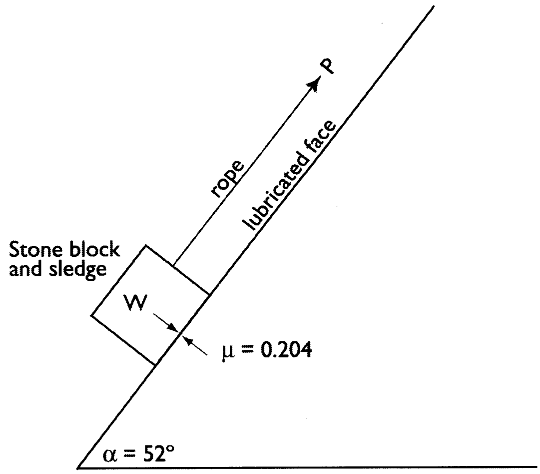

$$P = W(\mu\cos\alpha + \sin\alpha)$$
$$P = (Wb+Ws+Wr)(0.204\cos52° + \sin52°)$$

FIG. 2 Graphic representation of hauling forces.

about 2 tonnes, let us use such a block as an example in order to calculate the force required to haul it up one side of the pyramid. Let us make these further assumptions: that these core blocks were laid layer by layer and that the outer casing blocks were put into position on the faces up which hauling was taking place as each layer of core blocks was laid; that these outer casing blocks, which were of a harder and more durable material than the core blocks, would have been dressed by the stonemasons on their angled outside surfaces in order to provide a reasonably smooth surface for the blocks to be hauled up on; that they would have been made oversize so that enough material would remain to allow final dressing of the stones once construction had been completed. It is probable that the oversized angled profiles of the outer surfaces of the casing stones were undercut to provide a series of horizontal ledges that would facilitate the erection of scaffolding from which the final dressing could be achieved. It is also highly likely that the stones at each extreme corner of each course of blocks were cut to their final shapes as building work progressed; this would have ensured the geometrical accuracy of the four angled corners and provided a guide for the final dressing process of each separate face.

The force required to keep a sledge-mounted, 2-tonne block being hauled on a single 8-centimeter rope moving up an angled face of the pyramid is around $2^1/_2$ tonnes.[17] The maximum number of haulers required to

17. Consider the situation when the pyramid had reached half its completed height (about 74 meters above ground level). At this height each angled face would be 94 meters

sustain this force is about fifty.[18] A greater force would have been required in order to commence motion. This could have been provided by, say, four additional workers at the base of the pyramid. Such a team would be required anyway in order to deal with positioning the assembly and fastening the rope to it. Once the team had completed these tasks it would then, in conjunction with the hauling team of fifty men on the pyramid's plateau, prepare the assembly for its journey up the face of the pyramid and assist in providing its initial movement.

In order to provide the necessary lubrication at the interface between the block and sledge assembly and the outer casing blocks, water, which was in abundant supply from the adjacent canal and harbor complex, was probably poured down the face of the pyramid up which hauling was taking place.[19] Alternatively, a person of small stature, and thus light weight, may have ridden up with the assembly, applying lubricant from a vessel, as in the example of moving the statue of Djehuty-hotep. (The addition of a "lubricator" would not have had a significant effect on the required hauling force).

At the halfway point (about 74 meters high), the hauling team would

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long, and the flat plateau onto which the blocks would be hauled would be about 115 meters square. Assuming that a single 8-centimeter rope was used to haul one block up one face of the pyramid and that the block was mounted on a wooden sledge, the total weight W would equal the weight of the block plus the weight of the sledge plus the effective weight of the rope. If we stipulate 2 tonnes for the block, 0.3 tonnes for the sledge, and 0.5 tonnes for a 120-meter-long rope, we arrive at a value for W of 2.8 tonnes. We can substitute the estimated kinetic coefficient of friction from the previous examples, 0.204, and we know that the angle of inclination is 52 degrees to the horizontal. Thus, substituting in the formula

$$P = W(\mu\cos\alpha + \sin\alpha)$$

we see that

$$P = 2.8(0.204 \times 0.616 + 0.788) = 2.8(0.914) = 2.56$$

It should be noted that if the value of the kinetic coefficient of friction were doubled the resulting value of P would only increase by 13.7 percent, to 2.91 tonnes, which would require five additional haulers to sustain (see n. 18).

18. As with the example of transporting the statue of Djehuty-hotep, it is assumed that one man exerts a force equivalent to 68 kilograms. The number of men required to keep the block and sledge assembly moving up an angled face of the pyramid is $(2.56 \times 1000) \div 68 = 37.6$ men. However, this is for a hauling force which is parallel to the pyramid's face, whereas the haulers would actually be pulling in a horizontal direction across the pyramid's plateau. It is suggested that protective wooden battens were used at the point where the rope passed over the lip of the top outer casing block, and an additional hauling force would be required in order to overcome the frictional effects between the battens and the rope. This is difficult to estimate, although it may have accounted for an increase in force of about 20 percent, requiring a total hauling team of forty-five men. Allowing for contingencies, then, stipulate a maximum of fifty men.

19. Lehner (n. 1 above), 204–5. It is known, from archaeological evidence, that there was a harbor and interlinked canal system adjacent to the construction site, which were fed by the waters of the Nile.

have had enough available space on the plateau to have hauled the block and sledge assembly up the face of the pyramid and onto the plateau in one continuous movement. The assembly would have "tipped" easily onto the plateau due to the generous angle between the face of the pyramid and the plateau, and wooden battens were probably used to prevent the hauling ropes from fraying.[20] (It is possible that the outer casing blocks might have been covered with a latticework of wood over which the block and sledge assemblies were hauled). Once the blocks had reached the plateau, far less energy would have been required to move them into position than had been needed to lift them to the plateau. Levering techniques would probably have been used to remove the blocks from the sledges and position them accurately in their final locations. Obviously, as the height of construction increased the additional weight of rope would have had an effect, although not a significant one, and it would have remained feasible to lift blocks of up to about 4 tonnes on a single rope. Thus, the vast majority of the blocks used in the construction of the pyramid (the core blocks and outer casing blocks) could have been lifted using the methods described. For the relatively few heavier blocks within the structure it would have been necessary to use multiple ropes, with a corresponding increase in manpower in order to facilitate lifting.

Constructing the Great Pyramid

We have shown that the building blocks used to construct the Great Pyramid could have been hauled up a face of the pyramid. Using this approach as a reasonable model, we can now consider the probable building processes.

It would be reasonable to assume that a logical methodology was applied to the construction sequences and that a systematic approach was employed involving organized teams. We can only guess at what that approach might have been. Each team would have been responsible for hauling the blocks onto the plateau and then moving them to their final positions. Suppose that each team was assigned an area to work within and be responsible for. If this area were about 5 meters wide, it would have allowed sufficient room for teams to have kept clear of each other when hauling. This means that a 5-meter-wide "slipway" would have been assigned up a hauling face of the pyramid and then carried across the flat surface of the plateau. Let us consider the situation at different stages of the pyramids' construction.

When the pyramid had reached about a quarter of its height, the pla-

20. Apart from manufacturing protective battens to prevent the ropes from fraying, it is probable that joiners would have constructed many diverse devices in order to aid both the hauling and building processes.

teau would have been approximately 173 meters square and 37 meters above ground level. At this point each angled face would have been 47 meters in length. Approximately 1,327,100 blocks of stone would have been laid, accounting for about 58 percent of the volume of the completed pyramid. There would have been thirty-five 5-meter-wide slipways at this height, and, due to the size of the plateau, it would have been possible to simultaneously haul blocks up two opposing faces. The teams would have commenced by laying blocks at the center of the plateau and then working outward toward each hauling face. This would have produced a capacity of seventy blocks per lift at this height. As construction continued from the center outward the hauling teams would have moved onto the top of the current course of blocks in order to have effected lifting. This two-sided approach could have continued up to a height of about 40 meters, at which stage the hauling teams would have begun to intrude upon each other's hauling space, assuming that lifting took place in one continuous movement. Because on average each core block is about a one-meter cube, each hauling team would have been responsible for laying a course of blocks about 5 meters wide. At a height of 40 meters, over 60 percent of the volume of the pyramid would have been completed and approximately 1,400,000 blocks of stone laid.

An assumption at this stage is that a section of one of the faces not being used for hauling would have been kept free of outer casing blocks to provide a "stairway" for the workforce to climb to and from the plateau. Interior passages and stairs leading up and down to various chambers would also have served as temporary ways for the workforce to reach the construction site.

Between the heights of 40 meters and 74 meters (half the height of the completed pyramid) the hauling of the stone blocks could have been carried out up one face in a single continuous movement. At the halfway point the plateau would have been approximately 115 meters square, and each angled face would have been 94 meters long. Approximately 2,012,500 blocks of stone would have been laid, accounting for almost 88 percent of the volume of the completed pyramid. There would have been twenty-three 5-meter-wide slipways at this height, and upon reaching the plateau the blocks would have been taken to the opposite side of the plateau and laid back toward the hauling face, with each hauling team laying block in rows five blocks wide. The time taken to haul one block up the face of the pyramid at this point in the construction process would have been less than 3 minutes, as compared to 40 minutes for the ramp theory and 7 hours for the lever theory at this same point.

As the building work progressed, the plateau would have become progressively smaller, reducing the working area. Between 74 meters and 80 meters two ropes might have been used in order to maximize the working space. Two files would take up only half the length of a single rope hauling team, and the lift could still have been achieved in one continuous movement. At the 80-meter point over 90 percent of the volume of the pyramid would have been completed and approximately 2,076,900 blocks laid. Technically, the final 10 percent (by volume) of the pyramid would have been the most difficult to construct. Above 80 meters, the task of hauling the blocks up to the higher levels would have been more laborious as the surface area of the plateau decreased. As progress continued, it would be likely that the blocks would have been hauled up in stages.

Once all the building blocks had been positioned, the outer casing blocks would have required dressing in order to achieve a smooth outer surface. This not inconsiderable task was probably effected using wooden scaffolding from which the stonemasons could carry out their work. Chippings, assumed to be from this dressing work, have been discovered at the base of the Great Pyramid.[21]

It is difficult to estimate how much time was actually spent constructing the Great Pyramid. There would have been periods, as with any project of this nature, when inclement weather, illness, and the like would have delayed the building program, and some years would have been better than others from this point of view. However, based on the techniques described here we can make an estimate of the construction time.

With respect to the first 40 meters of the pyramid, we have seen that seventy blocks per lift for the core and outer casing blocks could have been achieved, assuming that two faces of the pyramid were used simultaneously. As the width of the base is 230 meters, decreasing at the height of 40 meters to a plateau 169 meters wide, the average number of 5-meter-wide slipways would have been forty each side between ground level and 40 meters. Given an adequate supply of blocks, there would have been a capacity to move forty blocks up one face in unit time. The next question to ask is, "how long did it take, on average, to lift and position the blocks?" An estimation can be made for this by looking at the sequence for one block, assuming that it had already been delivered to the base of the pyramid on its wooden sledge: (1) Connect the hauling rope to the block/sledge assembly, 10 minutes; (2) Haul the block/sledge assembly up the side of the pyramid and onto the flat plateau, 45 seconds assuming an average speed of 0.6 meters per second—say one minute; (3) Move the block/sledge assembly across the plateau, 5 minutes (again, at 0.6 meters per second); (4) Unload the block from the sledge, 10 minutes; (5) Position the block, lower the sledge and rope down to the base of the pyramid, and disconnect the rope from the sledge, 30 minutes. Adding up the individual elements gives an overall time of approximately 56 minutes for lifting and positioning one

21. Michael Jones and Angela Milward, "Survey of the Temple of Isis, Mistress of the Pyramid at Giza," *Journal of the Society for the Study of Egyptian Antiquities* 12 (1982): 139–51.

block. Allowing for contingencies, let us round this up to one hour per block. Therefore, for the first 40 meters of the pyramid's height, the time taken to lift and put into position the estimated 1,400,000 blocks would have been 1,400,000 hours. This time is, of course, for each individual block being dealt with as a separate entity. However, if, on average, eighty slipways were operational between ground level and 40 meters, then eighty blocks could have been processed at any one time. Therefore, the time spent on this section of the pyramid per team would have been 1,400,000 ÷ 80, or 17,500 hours. Let us assume that, each year, 10 hours per day for 320 days of the year were spent on construction. This would give an approximate time of completion for the first 40 meters of the pyramid of 17,500 ÷ (10 × 320) = 5.47 years. Allowing additional time for moving the larger, heavier, burial chamber blocks, it could be estimated that this element of construction took about six years—assuming, again, that lifting took place simultaneously up two opposing faces of the pyramid and that all the other work associated with building (quarrying, transport, and so on) also took place simultaneously. We can use a similar approach for the next 40 meters of construction, up to a height of 80 meters. The average number of slipways between these two heights would have been twenty-eight, with lifting taking place up one face only. Therefore, the time taken to lift and put into position the estimated 676,900 blocks in this section of the pyramid would have been 676,900 hours. (The time taken to haul the blocks up the face of the pyramid to a height of 80 meters would have been twice that for hauling to a height of 40 meters, but because of its reduced size less time would have been required to move the blocks across the plateau, therefore the same overall time of one hour has been applied.) The individual team time would therefore be 676,900 ÷ 28 = 24,175 hours. Applying the same building time criteria as before gives an approximate time of completion for the second 40 meters of the pyramid of 24,175 ÷ (10 × 320) = 7.55 years. Again, allowing some additional time for moving the larger blocks required for the burial chamber and passages, it could be estimated that this element of construction took about eight years. Thus, the estimated time needed to build to a height of 80 meters would have been fourteen years. From 80 meters to completion of the block laying would probably have taken, based on the previous assumptions, an additional six years, meaning that the entire structure would have been completed in twenty years.

Following completion of the block laying, there would then have been the task of dressing the outer casing blocks. This is very difficult to estimate but could well have taken a further two years to complete, assuming that work progressed on all four faces simultaneously. All this gives an estimated time for completion of the actual building work carried out on the Great Pyramid of twenty-two years. To this must be added time for preparing the site prior to building, setting out, building sledges, making ropes, and so on—say another year. The estimated completion time fits in with the generally held view that the Great Pyramid was completed during the reign of King Khufu, which is thought to have lasted for a minimum of twenty-three years.[22]

In order to keep up with the construction work, a constant supply of cut stone blocks would have had to be available. During the first 40 meters of construction, which was the most intensive, an average of eighty blocks would have been required every sixty minutes. The core blocks would have been delivered to the building site direct from the adjacent quarry, while the blocks from Tura and Aswan would have been brought overland.[23]

During the most intensive stage of construction, that up to the 40-meter point, it can be estimated that an average workforce along the following lines would have been required. For haulers and setters, 40 teams of 50 men times 2 hauling on the plateau, 40 teams of 5 times 2 setting the blocks, 40 teams of 4 times 2 working at the base, and 80 "lubricators," for a total of 4,800. During the building of the 6-meter-high pyramid in 1995, 12 Egyptian stonemasons quarried 186 blocks of similar size to those used for the core of the Great Pyramid in 22 days using iron tools. This equates to 0.7 blocks per day per man, or, over an 8 hour working day, 0.0875 blocks per hour. Compensating for less effective copper tools, let's say 0.07 blocks per hour for the ancient stonemasons. The time taken for the hauling teams to complete this stage of the pyramid was estimated at 17,500 hours per team, which is the overall time. Therefore, in this time, and using the adjusted 1995 work rate as a guide, one stonemason would cut 1,225 blocks (17,500 × 0.07). The total number of blocks within this section is estimated at 1,400,000 blocks. Therefore, it is estimated that the number of stonemasons would have been 1,400,000 ÷ 1,225, or 1,143—say 1,200 men. As well as stonemasons, there would have been workers removing and transporting the blocks between the quarry and the pyramid. The sequence of transportation would have involved a round-trip estimated to have taken around 60 minutes per block. For a rate of 80 blocks per hour, and a team comprising 12 men, 960 workers would have been required (80 × 12), so say 1,000 men. Obviously, there would have been many other workers involved with the construction process: joiners making and repairing the wooden sledges and other devices; rope makers making and repairing the necessary ropes required for hauling, water carriers, surveyors, supervisors, additional quarrymen, purveyors of food, and so on. It could be estimated that perhaps as many as 3,000 people were involved in these ancillary activities.

These estimations do not attempt to include the workforce involved in transporting the outer casing blocks from Tura or the granite blocks from

22. Lehner, 206.

23. Eugen Strouhal, *Life in Ancient Egypt* (Cambridge, 1992), 173–82. In the case of the blocks from Aswan a fair proportion of the journey would probably have been via boat along the Nile.

Aswan. The figures do, however, attempt to convey some idea of the likely workforce at the construction site. Adding up the various elements gives an approximate total workforce in the immediate environs of the pyramid of about ten thousand people during the most intensive period of construction. It has been proposed that as many as twenty-five thousand workers were involved at the building site during the most intensive period of construction.[24] However, a significant proportion of this workforce would have been involved with building and maintaining massive construction ramps, which, using the methodology put forward here, would not have been required.

Conclusion

The method of construction for the Great Pyramid proposed here, using the angled faces of the structure itself as surfaces on which to transport the blocks used to construct the pyramid, provides a more logical and practical alternative methodology to the view that massive, separately constructed ramps were used to move the stone blocks. Apart from eliminating the need to build separate ramps, such a methodology is considerably more energy efficient and far less time consuming, as it removes the need for hauling teams to go trudging up and down ramps all day long because the teams would have remained on the pyramids' level plateau—where they may indeed have lived during the more intensive periods of construction. The proposition that every individual block was elevated into position using levers and packing pieces is also an unsatisfactory solution; such a process would have been extremely awkward and risky due to the numerous maneuvers involved with each individual elevation. As with the separate ramp theory, the lifting teams would have ascended with each block lifted, which is inefficient. It is therefore suggested that levering techniques were only utilized for assisting the builders in a very localized fashion, such as loading and unloading sledges and positioning the building blocks in their final locations. The proposal that a form of shaduf was used to elevate the building blocks is also deemed an impractical solution.

It is estimated that the Great Pyramid took about twenty-three years to complete, and that during the most intensive period of work around ten thousand people were involved in its construction at the building site.

It can be concluded, from contemporary technical evidence relating to the hauling of large blocks of stone, that the wall painting in the tomb of Djehuty-hotep at Deir el-Bersha is accurate in terms of the number of haulers depicted in it.

24. Lehner (n. 1 above), 225.