

Man fears time, yet time fears the pyramids.

Arab Proverb



Construction of the Giza Pyramids

By Burke Thomas

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I. Introduction

The Egyptian Pyramids are the greatest engineering achievement in the history of the world. Five thousand years ago, before the invention of computers, electronics, steam engines, iron, screws, or pulleys, and without knowledge of electricity, calculus, or hydraulics, a civilization for a hundred years devoted itself to the task of building mountains in the sand with the singular purpose of serving as a resting place for their pharaohs. During the years 2600-2500BC roughly 20,000 workers served year-round as skilled workers, engineers, carpenters, cooks, and masters of stone (or under slavery as a prisoner of war) while for three months during the annual flooding of the Nile hundreds of thousands, more than was enlisted in their entire army, would flock voluntarily from the Delta to aid as unskilled laborers. In all they pulled over 25 million tons of limestone and granite from their quarries to their eventual resting place as pyramids in the middle of the desert. The Chinese did the same in pulling together to build the Great Wall of 1500 miles to protect their civilization from a Mongol destruction. But the Egyptians built their pyramids in a time of peace, *after* the unification of Upper and Lower Egypt under one crown. Never before has a society been as motivated as in the ancient Egyptians lusting after the completion of pyramid after pyramid simply to serve as resting place for their deified ruler. And indeed, “Nothing more perfect mechanically has ever been erected since that time,” (Ferguson 92).

II. Developmental History

A. Early Pyramid Development Through Imhotep

Burial has been a human custom for at least twenty thousand years. Caves in France have been found with shallow graves containing human skeletons in the fetus position. Later archeological sites demonstrate deeper graves, face-up burial, and simple markings perhaps used to mark the person's final resting place. Ancient history shows a trend towards more ornate burial, including the introduction of grave goods, as society progressed and in general, the more significance the person has, the more elaborate his or her tomb has been (Jurmain 335-336). Simple gravestone markers evolved to larger and larger rock mounds, where eventually graves began to become a structural concern for the ancient Egyptians, around six thousand years ago. Because of the Egyptian belief in the afterlife and the ability to take one's grave goods with them, tombs started to grow larger to accommodate more of one's worldly possessions. The more important the person, the bigger tomb they would have constructed, for the more goods they could bury with them. Food, statues, furniture, jewelry, even boats have been found in and around these tombs. These ancestors of the pyramids, rectangular *mastabas*, were made of mud bricks. The tombs of high officials in pharaoh's court are still erect as large, football-field size mastabas today, (Figure A).

The pharaoh Zoser around 2630BC commissioned a court official to design and build him a unique burial tomb. The building of such a pyramid required two things which had never been done before: "the first was provided by a pacified and united country while for the second a unique human genius was required," (Mendelssohn 35).

The engineer's name was Imhotep. Although not of royal blood, his official title as a purely self-made man was "Chancellor of the King of Lower Egypt, First after the King of Upper Egypt, Administrator of the Great Palace, Hereditary Nobleman, High Priest of the Heliopolis, Builder, Sculptor and Maker of Vases in Chief", and he was an engineer before the word ever existed.

Rarely has the world seen such genius as existed in this man. He developed and controlled the logistics of turning an uneducated group of thousands of men into a well-organized workforce capable of producing what was to be the world's tallest pyramid by a factor of twenty. He solved many of the problems that even later architects had difficulty with, including the balance of the lateral forces associated with a gigantic pyramidal weight pressing down on a square base. His masons slanted the inner stones of Zoser's pyramid towards the apex to help balance this out (Figure B), a technique that was grossly overlooked in the later Meidum pyramid. Imhotep's step pyramid was the first completely stone structure in the history of the world, and it is the oldest surviving one today.

The precursors to this step pyramid were almost trivial: a few tons versus a million of quarried stone. "One important innovation was the use of stone, which had been used sparingly in previous times," ((Fakhry 5). Imhotep built Zoser's pyramid *entirely* of blocks and stone. This fact alone, and the fact that Zoser's pyramid is still standing, means that Imhotep encountered and solved problems that, as most likely the first to attempt this in history, were unique to him. The problems of building on a larger scale were later reflected in Galileo's observation that a working model does not

necessitate a working structure; smaller mastabas did not necessarily need this lateral-support buttressing, but the stacked mastabas of Zoser's pyramid did. He also was a master of logistics, for pyramid construction of this magnitude required a similarly huge workforce. As F.M Barber puts it, "few men could have had a more difficult task since the world was created." (70).

Unfortunately his organizational specifics are still unknown, because, except the structure itself, any records of his thoughts are either destroyed or as of yet undiscovered. What little information we have on organization is from inscriptions on pyramidal blocks designed to be unseen from the outside, which dismantling of the outer limestone casing has revealed. When completed, Zoser's step (Figure C) had a base of 125 by 110 meters, rose to a height of 60 meters, had a burial chamber 28 meters deep, and was completed around 2630BC, just 75 years before the Great Pyramid. This was the first significant pyramid in Egyptian history.

B. The Great Failure at Meidum and its Consequences

The next structure of interest in the development of the Egyptian pyramid is the Meidum pyramid, which around the year 2600BC collapsed during the third stage of construction, the alignment of the outer walls [construction stages are mentioned in detail later in this paper]. When a structure fails it fails because of an error in design, and oftentimes this design flaw can be recognized and fixed so that the next structure is less likely to fail in this same way. The Meidum was a true pyramid, in that its outward shape was a tetrahedron. Unfortunately, whether by reason of carelessness or laziness or simple

lack of knowledge, the interior support for the pyramid partially collapsed and part of at least one pyramidal face was shorn off and to this day there are massive rubble mounds beneath the base of the pyramid. As the infamous Hyatt-Regency Hotel taught us in 1981, with even a seemingly small change, such as changing the position of the screws on a catwalk, or adding an outer casing to a step pyramid, you must recalculate the system.

Another key piece of evidence of this great failure is in the construction of the so-called “Bent” Pyramid (Figure D). This pyramid was being built at virtually the same angle, 54 degrees, as the pyramid at Meidum, but then abruptly tapers off to a shallower angle of 43 degrees 50 meters in the air. Although none of this can be absolutely proven, this would certainly be great circumstantial evidence that the catastrophe at Meidum caused the architects of the Bent Pyramid to reassess their construction and change the angle of ascent. A smaller angle would mean less height and weight, both of which are factors that contribute to greater instability. Many people would consider this irregularity in angle less structurally impressive than a uniform pyramid rising to the heavens. Through this point, coupled with the fact that there are no known collapses of pyramids built after Meidum, we can surmise that something changed structurally to allow the building of the three great pyramids at Giza.

Indeed, something did. Imhotep’s buttresses, while always at the base step pyramid of other true pyramids [discussed later], were not extended to include the buttressing of the structurally significant outer casing. Pyramids built later than Meidum demonstrate this slanting of the outer casing. Later foremen seem to have understood that

the beautiful limestone covering of their pyramids held significance in structure as well as architecture.

C. The Greatest Pyramid

The Great (Khufu's) Pyramid at Giza is one of mankind's most monumental legacies (Figure E). Caliph Malek al Azis Othman in 1215AD ordered the destruction of the Great Pyramid, but gave up after eight months with progress that wasn't even noticeable (Mendelssohn 85). It is necessary to understand the size of the Great Pyramid to appreciate its structural greatness, and Ahmed Fakhry puts it best in his study The Pyramids when he notes:

“Many persons feel that no mere description can do the Great Pyramid justice or even convey an idea of its enormous size. Statisticians have worked out several painstaking calculations in order to compare its height and bulk with other well-known monuments. According to their estimates, the area of the base of the Great Pyramid could contain the Houses of Parliament and St. Paul's Cathedral and still leave a large space unoccupied. Other calculations reveal that the area of the base would contain the cathedrals of Florence and Milan, St. Peter's in Rome, and St. Paul's Cathedral and Westminster Abbey in London. If all the stone in the pyramid were sawed into blocks 1 foot square and these blocks laid end to end, they would stretch two-thirds of the way around the earth at the equator. During his campaign in Egypt, Napoleon calculated that the Great Pyramid and its neighbors contained enough stone to build a wall 3 meters high and 1 meter thick which would entirely surround France. A mathematician among the various savants accompanying the expedition confirmed Napoleon's calculations.”

Ahmed Fakhry, The Pyramids (117)

Truly the Great Pyramid is a man-made mountain.

Herodotus said that the Great Pyramid took 30 years to build, (ten for the causeway), with “100,000 men labored constantly, and were relieved every three months

by a fresh lot”. This is the first written reference to the Egyptian pyramid, one that might have been shoddy after over 2,000 years of oral tradition. The first sign that this quote may be a misconstruction is the word “constantly”: although possible it seems impractical for such a group to work at night for the issues of safety and, obviously, light. The fine points of loading and unloading would have proved more difficult in the dark of night as opposed to under the bright midday sun. Also, it is unlikely that such labor would remain constant from season to season. (Mendelssohn 145). The more likely explanation of Herodotus’ observations is the allowance that it makes more sense that the three months he was referring to is seasonal rather than cyclical. As an agricultural people, the Egyptians for three months a year came to a standstill when the Nile delta flooded. The famous flooding, crucial in providing the soil with a year’s worth of fresh nutrients, did not allow agriculture during a quarter of the year.

This lack of food, coupled with the sudden idleness, no doubt compelled men to seek out sustenance for their families. This is the cornerstone of the theory that there was little slave labor involved in the pyramids. In fact, “ancient Egyptian history provides no evidence at all to support these stories” of slavery of workers, at least besides prisoners of war (Fakhry 103). Khufu reigned during a time of relative peace, when a standing army was less necessary. In fact, if most of the pyramid laborers worked voluntarily, there would be only a small demand on society for any army at all except defense. In other words, the workers of the pyramid were a group of citizens coming together in time, under their own free will, one of their purposes being to construct a monument worthy of their pharaoh. The praise of the ingenuity and work ethic of this force is great. F.M.

Barber states that, “Unlimited human labor being given, the appliances of the present time would be of small advantage to the architect” (Barber 51). i.e. the Egyptians did it the best way possible. The Great Pyramid was planned and built in thirty years – five thousand years later a much smaller project, the Brooklyn Bridge, took fourteen. Not only were the unskilled incredibly industrious in carrying out the brute work, but the skilled stone masons also were more than commendable. Art Bell claims that “modern technology cannot place such 20-ton stones with greater accuracy than those in the Pyramid”, an accuracy so great that you can’t fit a hair in between the limestone casing blocks (<http://www.europa.com/~edge/pyramid.html>). Khufu’s pyramid is 230 m square and 150m tall, with 6.5 million tons of limestone. Geometrically this gives an angle of 51 degrees 52’, with its circumference and its height being in a ratio of $1/2\pi$, accurate to the fifth decimal place, 3.14159.

It was not that an entire civilization came together to build these monuments, but instead that an entire civilization came together *because of building* these monuments. The building of the pyramids were unifying for Egypt: “working together, under one administration, their differences and mutual suspicions were bound to lessen” (Mendelssohn 153). This was voluntary work for a common goal and it ushered in an enlightenment in Egypt. Never before had a society advanced to this state in government. “These man-made mountains are a monument to the progress of man into a new pattern of life, the national state, which was to become his home for the next 5000 years,” (Ibid). The organization and completion of the pyramids changed the face of the world forever.

D. The Decline of the Pyramid Age and Graverobbing

The Pyramid Age thrived proportionately with the size of its workforce. The fervor and pride in building larger and larger pyramids depended on it and without workers, pyramids construction no longer became a national pastime. Egyptians instead focused their efforts on more immediate things, like the governance of its newly birthed nation-state. Ironically, the industrial fervor seems just to have faded away. Perhaps this was due to an intense feeling of pride, or the notion that if it took thirty years to build the Great Pyramid, another generation didn't want to start work on a larger pyramid, never to see its fruition. And with the trend towards smaller pyramids (and thus smaller workforces) after the completion of the Giza Pyramids, the Pyramid Age ended just three hundred years after its arrival.

Because of grave- and stonerobbing, unfortunately we are left with little information regarding the Egyptian pyramids and their construction today. When the architects of the pyramids built their elaborate false passages and hidden entrances, they were designed to befuddle a pack of mischievous treasure-seekers. The architects "evidently had not envisaged any long period of lawlessness during which local chiefs had leisure to mount sustained and large-scale operations" (Mendelssohn 58). The governance of the new nation state was not strong enough to keep the throne untainted by controversy and around the year 2000BC, upon the death of a pharaoh who had been ruling for over ninety years, chaos for rule ensued. This presents a huge problem in terms of people dedicated enough to one possible king to work solely on his burial chamber. Lawlessness ensued after the sixth dynasty collapsed and there was no longer any clear

ruling power. Thus most graverobbing happened 4000 years ago, for a span of 200 years. This proves problematic because it destroys much construction evidence and/or any blueprints that may have existed. The true mystery of the pyramids stems from graverobbing. The systematic deconstruction of the Giza pyramids around 2000BC left few tombs undisturbed and few limestone blocks in place. White limestone from quarries in Tura encased the Giza pyramids at one time, and supposedly allowed one to see them from the mountains in Israel. Now the only Tura limestone that remains is the cap of Khafre's tomb (Figure F), the majority of which long ago was hauled off to build the infrastructure of Egyptian cities.

This is not to say that the pyramids will ever be deconstructed. Kurt Mendelssohn relates a story where in 1215 AD the Caliph Malek al Azis Othman ordered the destruction of the Merkura pyramid. The Merkura pyramid is that of Khufu's grandson, and is the smallest of the Giza pyramids by a factor of ten. After collecting a large group of countrymen, the Caliph ordered the task abandoned after eight months, reporting that the stones were "scarcely missed". In fact, the Arabian historian Abd al Latif said that 'only on one of its sides can be noticed any trace of the impression which it was attempted to be made,' (Mendelssohn 85). It seems despite the best efforts of many, the pyramids will be with us for a long time to come.

III. Construction

E. Steps to Building a Pyramid

The success of Zoser's step and the failure of the pyramid at Meidum laid out a blueprint followed rather regularly for the remainder of pyramid construction in Egypt. The first problem was quarrying: stone had to be removed from the earth and shaped into workable blocks. The second, transport: the Egyptians drew much precedence for their pyramid-stone transport from their earlier work with colossuses and obelisks. There was then the problem of raising the stones up a certain height. This was accomplished by two simple machines: the lever and the inclined plane. Workers then erected a structurally sound step pyramid to act as a base for building the outer case. To help align the outer walls as they were built towards an apex, a pole, probably of iron, was placed to signal the desired meeting place for the four converging walls. Then white limestone was cut to size and placed on the outside to form a beautiful, shining, stable pyramid.

F. Quarrying

As aforementioned, the workforce of the pyramids contained thousands of skilled workers in addition to the seasonal muscle brought on by the rainy season. Many of these artisans were involved with stonework. Without the use of jackhammers or drills, these talented specialists separated stone blocks from the earth with amazing precision. Since stone can hold under intense compression forces but becomes brittle under far lesser tension forces, the stones were broken by pushing them apart. Stonemasons would, with iron or copper chisels (Figure G), hammer out a chunk of rock and inserted a

wooden wedge in the crack. When the wood was wetted, it would expand and, if the grooves and wood were strategically placed, snap off a desirable chunk of stone. The same types of machines used to raise the blocks to the top of the pyramid were probably used to transport the stone up and out of the quarry.

G. Transport and the Inclined Plane

Egyptians understood the later principles of Archimedes involving buoyancy, as evidenced by their transport of obelisks weighing as much as 350 tons before the construction of the pyramids (as an interesting engineering note, eight hundred years later they were effective in transport of the statue of Ramses II, which was made of a single piece of stone and weighed over 1000 tons). The Egyptians are no stranger to the transport of stone, and no doubt they found quite quickly that barges were far more efficient than dragging in terms of human power. The quarries most likely had an inclined plane, or at least a causeway, leading to adjacent harbors on the Nile. The barges and their precious cargo were maneuvered down the Nile River to another harbor close to the current pyramid project. It was there they were ready to begin their ascent up the inclined plane.

Most writers agree that the Egyptians had no knowledge of the pulley (Fakhry 9): the only two machines recorded in their mosaics are the lever and the inclined plane. After their journey down the Nile, the stone blocks were offloaded from their barges onto an inclined plane built right up to the dock. This inclined plane, with a slope as little as 1 in 3,000 (Barber 96), led all the way up to the pyramid of interest (Figure H). The ramp

was made at least partially of mud brick, the same which had been used to construct the earlier mastabas, and Herodotus mentions that construction of the Great Pyramid's ramp took ten years – fully one-third of the time it took to complete the entire project. As the pyramid grew, so did the necessity for a higher ramp, and dirt or bricks could simply be mounded on top of the existing one to reach these new heights.

As mentioned before, humans were the primary source of labor for these efforts. F.M. Barber dryly mentions, “Why employ an ox when five men can live on the same amount of food?” In terms of economy, however, “man power would be cheaper than oxen power for a twenty years' contract in hauling such stones” (37) - remember too that humans would have to be set aside to watch over the ox's efforts. Stones would be moved onto sleds to make this long journey to the pyramid. As few as 70 or as many as 1400 men are estimated to have been necessary to pull a given block forward (Barber 30). Mosaics have shown liquid being poured on or under the rudders, because not only was friction a problem, but also was the wooden rudders catching on fire from the force! These liquids could have been oil or grease to act as a lubricant, or milk or water to act as a flame retardant (Fakhry 12). Regardless, we know that Egyptians understood the fundamental concept of friction and sought to lower the sled's coefficient of friction.

H. The Final Product

The pyramid was then erected in what was hoped to be a structurally sound way. Imhotep understood that the buttressing must be inward, towards the apex, to account for the lateral pressures of a huge weight resting in such a shape. The builders at Meidum

were lax on this technique, and they paid for it. But luckily somebody in history figured out how to construct a pyramid in a method that has been structurally safe after five thousand years. At the end of the inclined plane it is hypothesized that a lever-crane was positioned so that workers could pull with many ropes on one side and lift up the attached block with the other (Figure I). This would allow one central gathering place for the stones, with the ability to maneuver them to other positions in the pyramid. And as credit to the genius of the stonemasons the final blocks, the white Tura limestones, were so carefully cut that today not even a postcard can fit between them.

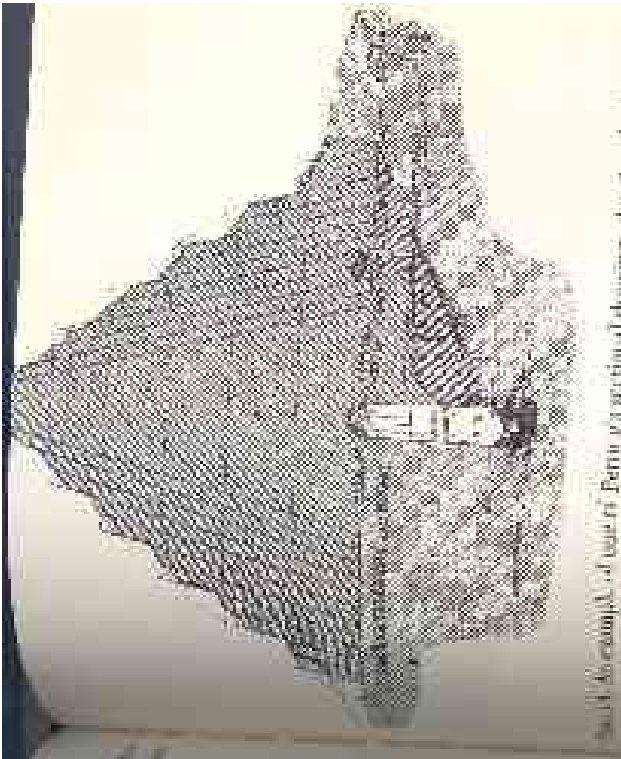
The end product can be seen from the moon. From the rows of desert mastabas to the mountains in the sand, the evolution of the Egyptian pyramids was a process that changed the landscape and destiny of the world forever. How a society accomplished this five thousand years ago still boggles the mind to the extent that many answers can only be surmised by even the most learned experts. As a nation Egypt accomplished a feat as of yet unparalleled in human history, one that transcends engineering and time to remain the only surviving wonder of the ancient world.

IV. Appendix

A) Mastabas



B) Interior Buttressing of Zoser's Step Pyramid



C) Zoser's Step



D) Bent Pyramid



E) The Great Pyramid



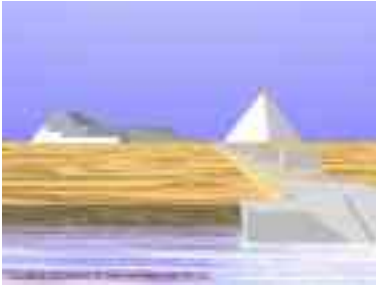
F) Khafre's (Great) Pyramid



G) Quarrying with metal tools



H) Ramps



I)



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