A New Consideration of the Construction Methods of the Ancient Egyptian Pyramids

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Abstract

Despite the wealth of books and articles published on the pyramids of the Old Kingdom, and the wide variety of suggestions offered with reference to the construction process itself, timing of the building schedule, technical devices, and workforce employed, no conclusive explanation has been proposed so far.

All previous solutions involving ramps start from the assumption that the blocks were hauled up by means of sledges pulled by bulls or man-power. Such a transport method requires long ramps with moderate inclination and large sledges; moreover, it raises the question whether enough workforce was available. Hardly any convincing suggestions have been made to explain how the works at the top were carried out or how the casing was dressed, nor are there any convincing building time calculations. The main shortcoming of the previous publications seems to be that archaeological findings are often not considered sufficiently.

I argue that for several reasons, perpendicular and spiral ramps are not likely to have played a significant role in the construction of the Old Kingdom pyramids. Rather, from the pyramid of Menkaure onwards, steep ramps erected parallel to the sides of the core steps were used to haul up building material with winches (*rollers*)*. In the following building phase, a working platform was attached to the pyramid's faces to enable safe laying of the casing, setting of the pyramidion, and dressing of the casing blocks starting from the top, as they had been left in boss during laying.*

Finally, schedule calculations are made for the construction of the Red Pyramid and the Pyramid of Khufu. The resulting building times agree with the time frame currently suggested for the reign of the respective rulers, and the building times as far as they are known today.

The pyramids of the Old Kingdom have always fascinated visitors of Egypt by their astonishing size and the vast proportions of the stone blocks. Not only do they leave a lasting impression, but they also prompt questions such as why did the ancient Egyptian kings build such gigantic burials? In searching for answers, we have grown accustomed to viewing the construction of the pyramids in the context of the religious mindset and the society of the time, and also in relation to the technical facilities and logistic proficiency of the ancient architects.

Throughout the past centuries, Egyptologists, archaeologists, engineers, and amateurs have attempted to explain the techniques and processes involved in the construction of the pyramids. However, as Egyptologists and archaeologists are not usually specialized to deal with the technical aspects of the construction process, many assumptions widely acknowledged in the academic world are flawed in this respect. On the other hand, authors without conventional training in Egyptology have made interesting contributions to the discussion of construction issues, adding remarkable explanations and calculations, but frequently they have overlooked important archaeological evidence.

Consequently, the suggestions of "non-archaeologists" are, as it were, less than well accepted among academic Egyptologists.

With reference to issues such as construction process, timing, technical devices, and workforce employed in the construction of the pyramids of the Old Kingdom, no conclusive explanation has been proposed so far, despite the wealth of books and articles published on the subject. In the present study I shall suggest a new solution to the construction of the Step Pyramids[1] of the Old Kingdom, starting from current research in Egyptology and taking into account archaeological evidence, taking particular care to avoid internal contradictions. I base my analysis on the following assumptions:

- Only tools, transport devices and construction techniques proven by archaeological evidence to have been available in the Old Kingdom can sensibly be assumed to have been employed.
- The archaeological evidence pertaining to the pyramids of the Old Kingdom should be taken into consideration comprehensively.
- Any explanation should relate to the construction of the entire pyramid, including the setting of the pyramidion and the smoothing of the casing.
- Building time calculations should be presented for all pyramids discussed.
- Aspects of construction technique and safety issues should be considered for the construction process as well as for subsequent dressing.
- Backsighting must have been possible on a regular basis throughout the building process; therefore, accessibility must have been guaranteed.

Construction Techniques in the Old Kingdom

The laws of statics and mechanics were neither explored in theory nor by scientific experiments throughout the Old Kingdom. There is no evidence for any sort of static reckoning similar to that which we are accustomed to today. Proficiency in construction, as in other crafts, was developed through observation of nature and by experience, and thus brought to perfection. The techniques employed in the production of columns, architraves, obelisks, and so forth, as well as the relevant means for building and transport, continued to evolve, culminating in the Late Kingdom. For example, alterations in work processes or construction techniques would emerge on the grounds of experiences made with different types of material like local bedrock. Indeed, if one may say so, solutions to construction issues tend to be as "simple" as the available techniques.

On the other hand, the construction of the pyramids is unthinkable without extensive preparation and detailed plans. Exact schedules for each task and a highly sophisticated infrastructure were indispensable. Choosing quarries yielding adequate material and finding a site suitable as a harbor for the shipping of material, surveying the pyramid's base area and orienting it, calculating and providing, marking and storing of building material were tasks that required an experienced and exceedingly well-organized team. We have evidence that in the Middle Kingdom stone blocks were inscribed with precise descriptions comprising the date of production, the mason in charge, the transport pathway, the storage area, and so forth.[2] It seems reasonable to assume that a comparable level of organization also existed in the Old Kingdom.

Preparations for work in the entire construction area required painstaking organization. Similarly, regulations were needed for transfer of material from the quarries and the harbor, and also for the

[1] With the term "Step Pyramids," I refer to buildings with a stepped core, resembling a series of platforms built one on top of the other, each smaller than the preceding one. The outer walls of the steps consist of large, finely hewn blocks with a batter of about 80°. To fill the core, stones of varying format were used, and also rubble, gravel, tafla, and mortar.

[2] Felix Arnold, *The Control Notes and Team Marks. The South Cemetery at Lisht* (New York, 1990), 14.

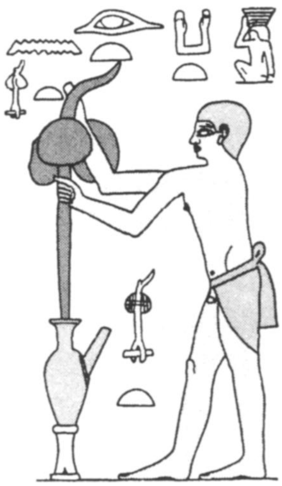

Fig. 1. The workman from the tomb of Ti (drawing after Steindorff, Das Grab des Ti [Leipzig, 1913], pl. 134).

recruiting and maintenance of the workforce. Just looking at the number of blocks and the building time as such, we must inevitably conclude that some sort of "just in time" principle was employed to coordinate quarries, harbor, storage, and building site. Unfortunately, no construction reports are available for the Third and Fourth Dynasties. However, a pictorial representation from the tomb of the royal architect Senedjem-jb Inti, dated to the late Fifth Dynasty, can be regarded as proof that the owner of the tomb was in charge of a plan for the pyramid complex of King Djedkare Isesi.[3]

Considering the life expectancy of the ancient Egyptian rulers, the building schedule for the pyramid complexes was extremely tight. Works at several stages of construction must have been carried out in various areas of the site at the same time.

Much information pertaining to ancient Egyptian craftsmanship can be found in pictorial representations, notably reliefs in tombs of the kings' relatives and officials. Such representations can be compared to other archaeological evidence, and conclusions can be drawn with reference to the reconstruction of long-forgotten techniques. Below, I shall discuss some construction techniques that have emerged from such research with reference to the relevant archaeological findings and sources.

Notably, the sarcophagus of Khufu, the first known sarcophagus of the Old Kingdom to be made from granite, has been extensively studied, and it has been proven that copper saws in combination with sanding were used to accomplish its remarkable exterior design.[4] Further to this, Stocks has published an in-depth study of the usage of saws, including documentation of experimental approaches and other aspects of stone working.[5]

Drills are shown on various representations from the Old Kingdom period. Borchardt, for example, refers to a picture of a drill for carving hollow vessels from the Fourth Dynasty. The drill has a forked shaft, and pieces of flint could be inserted as drill bits depending on the required diameter. At its upper end, an arched crank handle is attached, together with two stones on ropes that serve as weight and flywheel at the same time. If pressure is kept constant, the stone weights assure an accurate centering of the drill's working end. In the tomb of Ti in Saqqara, a workman is depicted with a drill of this type (fig. 1).

The simplest lifting device attested from the Old Kingdom onwards is a wooden lever beam. It enables the user to lift heavy weights attached to the shorter arm with relatively little force by moving the longer arm of the lever. This method was used to loosen stone blocks from the bedrock in the quarries of Giza, and also for laying and adjusting stones for the pyramid's core and casing.

The usage of drills and lever beams bears witness to the fact that in the Old Kingdom, ***the functioning principle of cranks and rollers*** was already understood and put to practical use; the principle of ***force intensification*** was therefore known implicitly.

Rollers with rods positioned at right angles for power transmission (spills, winches) are also known to have been in use for ***lowering*** and ***lifting*** of heavy weights throughout the Old Kingdom. For example, in the upper part of the antechamber of the pyramid of Khufu, semicircular grooves can be

[3] Rainer Stadelmann, *Die großen Pyramiden von Giza* (Graz, 1990), 248.

[4] Denys A. Stocks, "Stone sarcophagus manufacture in Ancient Egypt," *Antiquity* 73 (1999), 918–22.

[5] Denys A. Stocks, *Experiments in Egyptian Archaeology. Stone working technology in Ancient Egypt* (London, 2003).

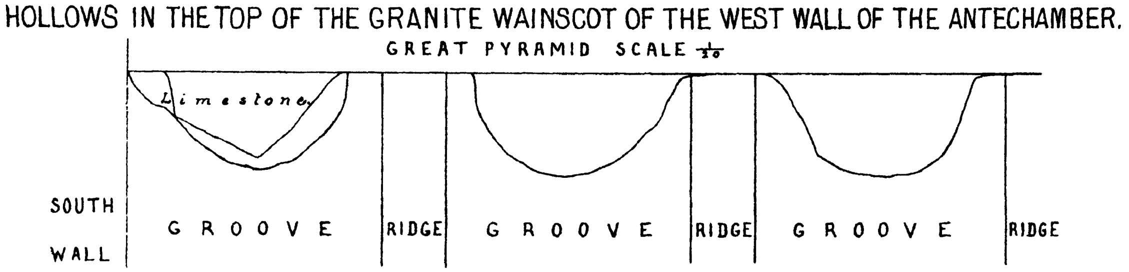

Fig. 2. Grooves in the wainscot of the antechamber in the pyramid of Khufu (drawing after Petrie, Pyramids and Temples of Gizeh, pl. 12.).

seen in the wainscot on the West wall, as observed by Borchardt,[6] and measured by Petrie (fig. 2).[7] If we interpret these grooves correctly, they served as rests for round cross beams positioned horizontally above the antechamber. These beams, or rollers, were part of a construction which was used first for controlled lifting of the plugging blocks in order to remove the supports, and then for lowering them to seal the tomb (fig. 3). Ropes were run through the plugging blocks, coiled around the roller beams, and lead towards the Grand Gallery.

The average weight of each of the plugging blocks is approximately 2.5 tons. The borings on these blocks suggest that ropes were run down through them and back up. As there are four borings to each block, each rope on either side would have held a weight of about 0.31 tons (half of 0.62 tons). If the ropes had a diameter of 5 cm, they had to bear a load of 15 kg/cm^2. The palm raffia ropes that were used at the time would have been adequate for such a load. If hemp ropes were used,[8] which are even more tear proof, and also attested for the Old Kingdom, a smaller diameter of approximately 3 cm would have sufficed. By means of several coilings, as seen in winches on sailing boats, even heavier loads could have been held with much less force than their weight would require without the aid of such devices.

This assumption is corroborated by the fact that the rollers' diameter (approximately 0.3 m) is unusually wide for its length (1.5–1.6 m), and much wider than the weight of the plugging blocks would seem to require at first sight. The ropes on the Southern side of each plugging block would carry a load of only half the plugging block's weight (approximately 1.25 tons). When the ropes had been tightened and the wooden supports removed from the ruts for plugging blocks, the ends of the ropes towards the South were uncoiled gradually as they ran across the respective roller several times, to lower the plugging blocks. It was possible to tighten the ropes in order to remove the wooden supports by moving one of the rollers against the lowering direction. The force necessary for this movement was achieved by moving rods that were attached at right angles with the axis of the rollers, as spokes of a winch or a spill. In the present case, a power transmission ratio of 5:1 is possible (length of the rods: max. 0.95 m, radius of the roller approximately 0.2 m) or 10:1 (0.95 m as opposed to a radius of approximately 0.1 m). This is to say that a force of a mere fifth (0.25 tons) or tenth (125 kg) of half of the weight of each plugging block (1.25 tons) had to be employed to tighten the ropes and start lifting the block. Then, the force needed for tightening the ropes—250 or 125 kg for a roller diameter of 0.2 or 0.1 m—could be easily achieved by four men working at the spill above the roller,

[6] Ludwig Borchardt, *Einiges zur Dritten Bauperiode der Großen Pyramide bei Gise* (Berlin, 1932), pl. 4.
[7] William M. Flinders Petrie, *Pyramids and Temples of Gizeh* (London, 1883), pl. 12.
[8] Björn Landström, *Ships of the Pharaohs* (London, 1970), 82–84.

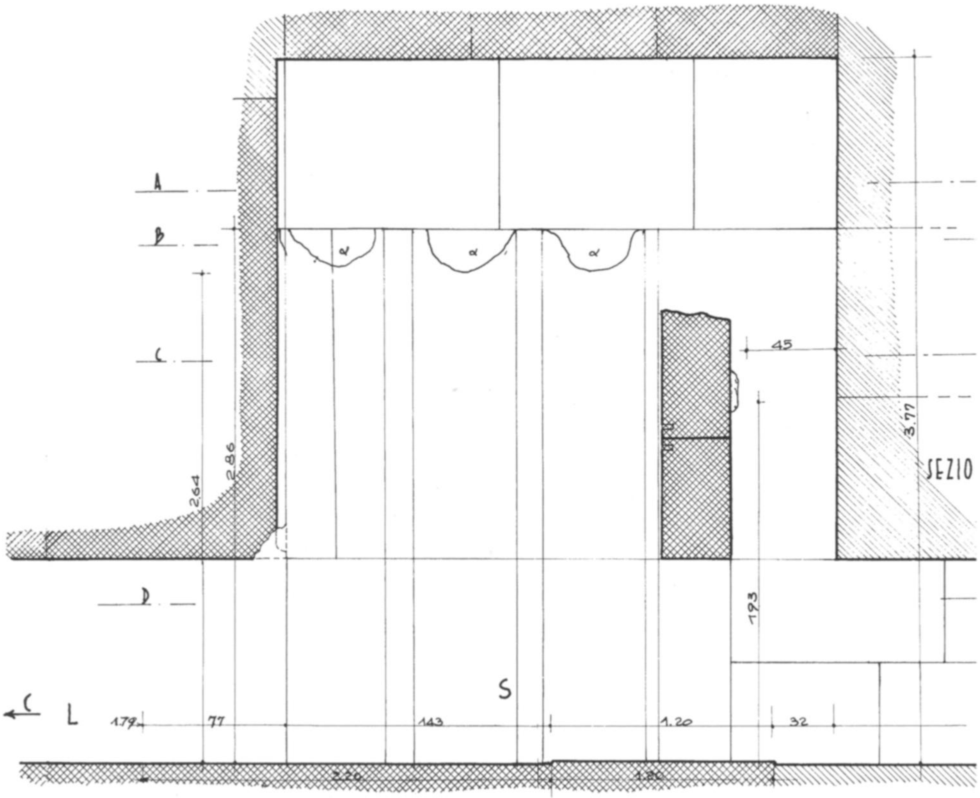

Fig. 3. Antechamber of the pyramid of Khufu (drawing after Borchardt, Einiges zur Dritten Bauperiode, pl. 4.).

together with further workmen pulling the rope's end in the corridor. A process such as this serves to explain why a gap of approximately 1 m was left between the roller and the ceiling. The pyramid of Khufu is the first building in which rollers were employed for controlled lowering of plugging blocks. Later, in the antechamber of the pyramid of Menkaure, the same principle was employed.

Therefore, the use of rollers with spokes (winches) should be taken into account when discussing lifting and lowering of loads and transport across inclined planes. Such connections between the various groups of archaeological evidence have not previously been discussed to satisfaction, *and in the absence of relevant material evidence, we are of course dealing with interpretations here*. However, it emerges that a well-functioning system of lifting devices must have been available in the Old Kingdom from the Fourth Dynasty onwards at the very least.

In fact, the combination of lifting devices and an inclined plane is virtually the only way of explaining how the gabled roofs in the pyramid of Khufu, or the burial chambers built in open cut construction as used in the pyramids of the Fifth and Sixth Dynasty, or even the gabled roof in the burial chamber of Djedefre in Abu Roash were built. This construction method even allows for adjustment to the varying weight of the loads, or the height at which the blocks were brought into their definite position: ramps sloping at various degrees, or several winches in a row could have been employed.

Building material and similar objects were conveyed on a ***level plane*** by means of sledges. Several pictorial representations from tombs of officials of the Old Kingdom show transports of statues and other goods on sledges. In a relief from the tomb of Hetepherakhti, a high-ranking official from

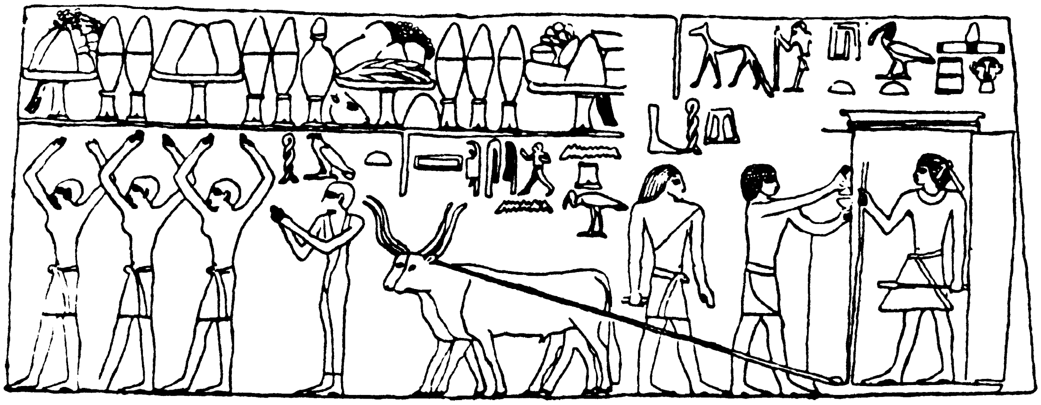

Fig. 4. Transport of a statue—two bulls pulling a carriage, from the tomb of Hetepherakhti (drawing after Mohr, The Mastaba of Hetep-her-Akhti, fig. 3).

Memphis (Fifth Dynasty),[9] two bulls are pulling a device possibly made from wood, upon which the statue is secured against falling or shifting (fig. 4).

One of the ***principles of Egyptian construction technique*** was to pull, rather than lift, large or heavy stone blocks. This was the case for transports to the building site, and for bringing the blocks into their definite position. An inclined plane, or ramp, was commonly used, as is attested by a remarkable number of Old Kingdom ramps connecting quarries and pyramid sites, and by the causeways.

Mostly, the angle of inclination is low so as to ensure that bull carriages and towing crews were able to move even very heavy blocks. Only the small Layer Pyramids of Lisht, Meidum, and Sinki have perpendicular ramps which were used in building the pyramid itself. Other than that, only ramps that delivered material to the area surrounding the immediate construction site are attested. No sufficient amount of ramp material has been found in the necropolis areas, not even in the case of pyramids that were abandoned in mid-construction.[10] Disposal sites attested in the pyramid area of Giza consist largely of a mixture of limestone, gypsum and tafla without any obvious remnants of Nile mud. They are usually interpreted as waste that was disposed of during the building of the pyramids.[11]

This being the state of archaeological research, one cannot but draw the conclusion that a building technique was used during the Old Kingdom which did not depend on perpendicular ramps that required enormous amounts of building material as their height had to be gradually increased throughout the construction process.

At this point, it is illuminating to take a closer look at the descending and ascending passages in the pyramids of the Fourth Dynasty. They can be regarded as steep ramps displaying a gradient ratio of 2:1 (horizontal : vertical), or a slope of 26°33′54″, with only minor exceptions to this rule. The size of the entrances (1.2 m width, 1.05 m height) argues strongly against the use of towing crews or bull carriages for conveying building refuse from within the pyramid, such as chippings from the rock core, towards the outside. Indeed, even granite slabs with a volume of up to 3.2 m length, 0.95 m width and 0.7 m height for the lower burial chamber, each amounting to a weight of up to 6.5 tons, were moved on this route. Hence, steep ramps are attested in the Old Kingdom.[12]

[9] Herta Therese Mohr, *The Mastaba of Hetep-her-Akhti* (Leiden, 1943), 36, fig. 3.

[10] Rainer Stadelmann, *Die ägyptischen Pyramiden* (Mainz, 1997), 226.

[11] Mark Lehner, "The Development of the Giza Necropolis. The Khufu Project," *MDAIK* 41 (1985), 124 and 132.

[12] Jürgen Becker, Die Funktion der Pyramidenkorridore als vermessungstechnische Einrichtungen, *Sokar* 6 (1/2003), 14–21.

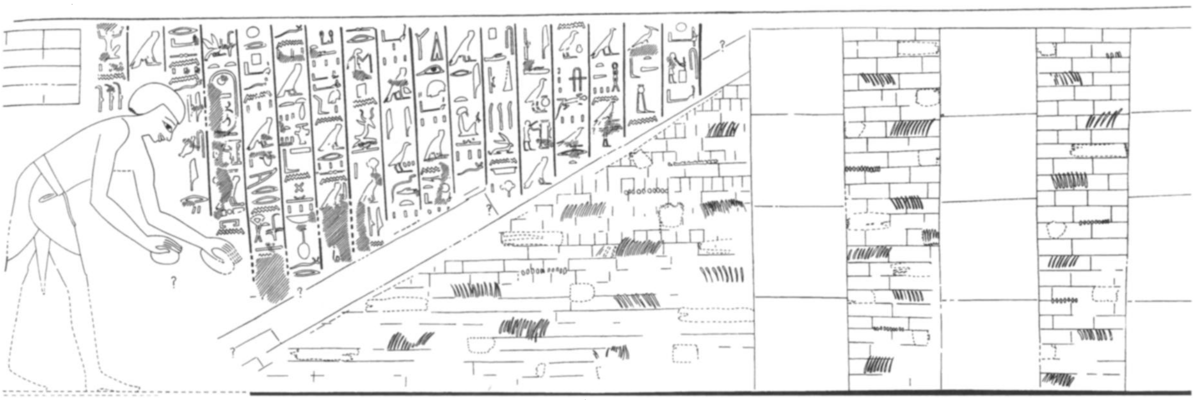

Fig. 5. Brick ramp from the tomb of Rekhmire (drawing after Davies, Rekh-mi-Re, pl. 60).

It is also interesting to consider the picture of a ramp from the tomb of Rekhmire (TT 100 Thebes West) although it is dated to the Eighteenth Dynasty (fig. 5). To the right, three walls or columns can be seen, the intervals between which are filled with brick walls. To the left, a ramp runs towards a building under construction, apparently enabling upward transport of stone blocks to the next layer. The gradient ratio of the ramp is 10:5, or 2:1 (26.5°).

Initially started as a mastaba, the ***Pyramid of Djoser*** was built in layers (two to each step), and is therefore rightly referred to as Layer Pyramid. The basic techniques for the construction of such Layer Pyramids were developed at that time. Blocks were arranged around the core, with inward-leaning layers. The pyramids of king Sekhemkhet and Khaba, of which only the stumps are preserved, and the small pyramids (possibly of Huni?) were built according to this principle. There is practically no evidence for a smoothed casing here.[13]

The first ***Pyramid of Seneferu*** at Meidum was built as a Layer Pyramid in several stages. In stage E1 and E2, limestone blocks were used for the visible surface of the steps, and dressed after application. After the finishing of the Layer Pyramid in stage E2, the steps were filled with another layer (E3), so that the facade now formed a constant slope, rather than a stepped outline. Afterwards, it was cased with finely grained limestone. In this monument, we are able to witness the transition from a visibly stepped Layer Pyramid to a pyramid with steps filled to form a facade with a constant slope ("true pyramid'). This development took place parallel to the construction of the Bent Pyramid. The cult pyramid of Meidum was also built as a Layer Pyramid.

It is virtually impossible to offer an archaeologically sound explanation for the construction process of the ***Bent Pyramid***, especially its inward structures. The start of its construction is usually dated to twelve to fifteen years after the start of the construction of the Meidum pyramid, and at this time, no severe difficulties had occurred with the Layer Pyramid style. It is therefore likely that the Bent Pyramid was initially designed as a Layer Pyramid as well. When the first stage of construction was completed, backing and casing blocks were added in the next stage to form a constant slope in its lower half. When the additional casing had been finished, the pyramid's construction was continued from a height of 90 cubits (47 m) onwards with a less steep slope. Moreover, the construction technique was modified: the stone courses underneath the casing were then set horizontally, that is to say the degree of inward leaning was lessened as the building gained height. Also, the stone blocks used were smaller than those used in the casing below.

[13] The casing of the lowest step of the small pyramid at Saujet el-Meitin is an exception to this rule.

The design of the attached Satellite Pyramid then followed the "new," modified construction principle with horizontal courses of stone blocks. This might have served as a test for the construction technique later adopted in other pyramids.

To sum up, the transition from the principle of inward-leaning layers, as seen in the Layer Pyramids, to construction by means of horizontal courses, the latter being characteristic for the Fourth Dynasty, took place during the reign of Seneferu. Having been pinned down to the building process of the upper half of the Bent Pyramid, the attached cult pyramid, and the Red Pyramid, it can be explained from the difficulties that occurred during construction of the Bent Pyramid.

The ***Red Pyramid*** is the first to display fully horizontal courses of casing blocks. Due to its good state of preservation, archaeologists have not been able to obtain any definite information as to the structure of its core. However, it is hard to imagine that the core would consist of inward-leaning layers after the disturbing experiences made during the building of the Bent Pyramid.

Another significant change took place during the construction of the Red Pyramid, because the large blocks familiar from the Giza pyramids are used here for the first time. Consequently, new transport techniques must have been developed for these blocks. Considering the chronology of Seneferu's reign, the pyramid's construction started relatively late, and it is possible that the builders were pressed for time, so that changes in the construction technique were at least partly dictated by tight schedules. If a pyramid is built with stepped core and casing, it is possible at various stages of construction to proceed on all four sides of the pyramid, so that much time can be saved. It is not a far-fetched thought that the first and foremost way of improving construction techniques to such a degree as to enable the building of the Great Pyramids was to collect solutions developed from difficulties encountered previously in this epoch characterized by intense pyramid building activity. Therefore, we may conclude that the core of the Red Pyramid consists of steps with horizontal courses, marking the beginning of the Step Pyramid style.

Scholars generally speak of a transition from the so-called Step Pyramids (as the Layer Pyramids are often mistakenly called) towards the "true" pyramid during the reign of Seneferu. However, the actual circumstances of this transition are hardly ever considered. Within eighty years after the erection of the first pyramid by Djoser, the "classic" pyramid was developed as the type of royal burial that should dominate the ancient Egyptian necropolis throughout the upcoming centuries. Seen from an evolutionary perspective, the development of Egyptian burial structures first started from the mud brick mastaba, moving on to the Layer Pyramid and the Step Pyramid and reaching a climax in the "classic" pyramid with a constant slope.

Observations made on the breach in the South face of the pyramid of Khufu and in the tomb robbers' tunnel on the North side, and also on the breach in the North face of the pyramid of Menkaure (fig. 6) suggest that the horizontal courses of the casing do not match those of the core. In both pyramids the filling within the core walls that form the steps consists of roughly hewn stones of various sizes and shapes piled on top of each other irregularly, and joined by mortar. Some of these are clearly unworked quarry stones.

Production, transport, and laying of the stones for the core would have required less effort than for the casing. The stepped core served to improve the inner stability of the building, while also increasing its resilience against external damage. However, the actual structure of the core of the Khephren pyramid remains unknown up until today.

The foundations of the casing were leveled out and measured permanently. The same is true for the other courses of the casing and their respective offset. It was essential to maintain the same height of the steps in order to achieve a constant batter. Depending on the quarrying, the stone layers may have had different heights. Under such circumstances, exact monitoring of the batter was the

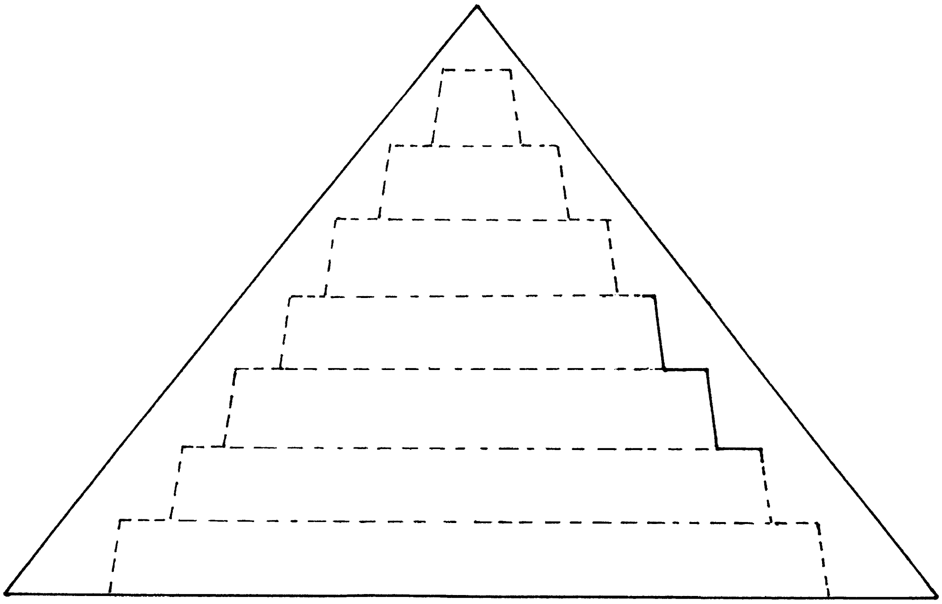

Fig. 6. Cross-section (S-N) of the pyramid of Menkaure with steps archaeologically attested in the breach on the north face (drawn lines) and the other steps of the core reconstructed by analogy (dotted lines).

only viable way to check the angle of inclination, on which the height of the pyramid depended. The fact that the pyramids' exact slopes vary is most likely a result of different designs, or else just slightly inexact measuring. Besides, it has to be admitted that today, the angle of inclination can often be only roughly determined due to the pyramid's state of preservation. It seems likely, however, that the actual height of the pyramid was not included in the initial design, rather, in effect, it resulted from the added offset of all steps.

The Step Pyramid style was kept in use throughout the Fifth and Sixth Dynasties, as is attested by archaeological findings on all pyramids of this period, including the cult pyramids and Queens' Pyramids. The pyramids of Menkaure and Userkaf mark the beginning of a period of pyramids with less monumental dimensions than those of the Fourth Dynasty. The development continued in this direction until the end of the Sixth Dynasty (Pepi II). However, the technique used in constructing the steps changed during the Fifth and Sixth Dynasty. The stepped core walls of the steps consist of an outer wall executed in well-hewn stones with slight batter, while towards the inside, we find a filling of blocks of various shapes and sizes that are only roughly hewn and mixed with mortar and rubble. Thus, by using smaller blocks, it was possible to lower the expenses for production and transport in comparison to the pyramids of the Fourth Dynasty.

The courses of large well-hewn stones casing blocks characteristic of the Fourth Dynasty pyramids disappear, making way for smaller backing stones of irregular shape filling the spaces between the steps and the outer limestone casing. As a result, when the casing was stripped, the mortar was exposed to the elements so that parts of the core masonry collapsed. Stadelmann, Lehner, and others speak of slack workmanship here; similarly, Maragioglio and Rinaldi attribute the state of the building to the inferior quality of the masonry. However, I should like to argue that this construction technique was the result of experiences made in pyramid building to the extent that in smaller pyramids, a stable outer casing would have sufficed to protect the core from weathering or erosion. Surely, experience in pyramid building would have become increasingly profound over the years. Moreover, in order to keep within tight building schedules while also minimizing the costs, the small pyramids did not receive such a closely-fitted casing as the pyramids of the Fourth Dynasty, whose inner casing masonry even resists the weather and most of the erosion when much of the outer casing is stripped.

To sum up, all pyramids of the Old Kingdom have stepped cores (layered or stepped construction).[14] In the immediate surroundings of the pyramids, no ramps have been attested by archaeological evidence that could have been used for building the pyramid itself rather than for transport of stone blocks to the construction area. The pyramid of Seneferu in Meidum is the one notable exception to this rule.

The pyramids of the Old Kingdom were planned and built over a period of roughly four hundred years, and a broad spectrum of construction techniques must have been invented and applied, while the techniques themselves were improved continually.

Some Previous Explanations of Pyramid Building

Nearly all explanations of pyramid construction have been formulated with respect to the pyramid of Khufu. As stated above, with a view to archaeological evidence, the techniques did not change much throughout the period of four hundred years (Third to Sixth Dynasty), during which roughly twenty-five pyramids were built, with the one notable exception of the transition from Layer to Step Pyramid during the reign of Seneferu. Other improvements were introduced in a less dramatic way and can hardly be traced nowadays. Therefore, we have good reason to assume that any theories on the building of the pyramid of Khufu should also serve to explain the building of other pyramids of the Old Kingdom.

An analysis of the suggestions published so far with reference to the building of the ancient pyramids in general, and the pyramid of Khufu in particular, yields the following three categories:

- solutions involving perpendicular ramps,
- solutions involving ramps built along the pyramid's sides, and
- solutions making use of lifting or towing devices.

Any discussion of the subject should fulfill the prerequisites listed below, otherwise it does not measure up to the requirements of the situation, and thus fails to meet the standards of academic discussion.

Basic prerequisites for solutions suggested for the construction of the pyramids

1. Only such tools, transport and techniques as are proven by archaeological evidence to have been available in the Old Kingdom are considered.
2. The archaeological evidence pertaining to the pyramids of the Old Kingdom is taken into consideration comprehensively.
3. The solution relates to the construction of the entire pyramid, including the setting of the pyramidion and the smoothing of the casing.
4. Building time calculations are presented in order to allow comparison with other concepts.
5. Aspects of construction technique and safety issues are considered for the construction process as well as for subsequent dressing.
6. Measuring must have been possible on a regular basis throughout the building process; therefore, accessibility must have been guaranteed.

[14] In the case of the Bent Pyramid, the Red Pyramid, and the Pyramid of Khephren, this has not previously been proven.

In order to briefly review the extant literature, I shall now present three types of solutions to the issues of construction techniques presented by the respective authors.

Perpendicular ramps as suggested by Arnold,[15] Stadelmann,[16] Lauer,[17] Lattermann,[18] and others ***can be excluded as a means of construction*** on the grounds of the following observations:

1. The ramps require continuous increase in height and, accordingly, width. This leads to regular disruption of the construction works, or at least considerable delays.
2. The volume of the ramps would have been enormous, easily reaching or even exceeding the volume of the pyramid itself, depending on the design of the ramp.
3. No archaeological evidence has been offered that cogently proves the existence of ramps or appropriately large rubble deposits.
4. Free-standing ramps built from clay or mud bricks sustain their own weight only up to a height of 120 m.
5. Archaeological evidence from the Step Pyramids, notably the pyramid of Menkaure, contradicts the hypothesis that the core was erected layer-wise, casting doubts on an idea that is crucial to the ramp models.
6. Due to safety concerns and aspects of construction technique, the application of the casing and dressing required scaffolding or other attachments to the pyramid's facade.

Spiral ramps, as proposed by Goyon,[19] Lehner,[20] Klemm and Klemm,[21] Houdin,[22] and others ***can also be excluded as a method of construction*** on the grounds of the following observations:

1. At the corners of the pyramid, spirals ramps would have necessitated transport of building material at an angle of 90°, even if the corners were chamfered. This was hardly possible, and even if it was, it would have been an excessively time-consuming task. Also, no feasible solutions have been offered as to the redirection of the traction force.
2. The idea that the core masonry was laid layer-wise is not corroborated by archaeological evidence.
3. The limited transport capacity of the spiral ramp leads to a schedule for the pyramids' construction that by far exceeds the attested time frame.
4. As stated above with reference to the other ramp models, due to safety concerns and aspects of construction technique, the application of the casing and dressing required scaffolding or other attachments to the pyramid's facade.
5. Exact measuring throughout the building process would have been difficult as spiral ramps are thought to have enclosed the pyramid, partly obscuring its outer face and corners. It would have been very difficult indeed to ensure a constant batter.

Furthermore, the authors suggesting ramps often omit calculations of transport capacities, thus failing to set their solution in relation to the time frame suggested by archaeological evidence, which in the case of the pyramid of Khufu is a maximum of twenty-three years total.

[15] Dieter Arnold, "Überlegungen zum Problem des Pyramidenbaus," *MDAIK* 37 (1981), 15–28.
[16] Stadelmann, *Giza*, 266–275.
[17] Jean-Philippe Lauer, "Le problème de la construction de la grande pyramide," *RdE* 40 (1989), 91–111.
[18] Walter Lattermann, *Der Bau der Cheopspyramide* (Munich, 2002).
[19] Georges Goyon, *Die Cheopspyramide* (Augsburg, 1990).
[20] Lehner, "Development," 109–43.
[21] Rosemarie Klemm and Dietrich Klemm, "Die Integralrampe als Konstruktionselement großer Pyramiden," in H. Guksch, ed., *Stationen. Beiträge zur Kulturgeschichte Ägyptens. R. Stadelmann gewidmet* (Mainz, 1998), 87–94.
[22] Jean-Pierre Houdin, *Cheops. Die Geheimnisse um den Bauprozess der Großen Pyramide* (Mainz, 2007).

The solutions offered by Arnold,[23] Isler,[24] and Graefe,[25] who propose ***constructions involving steps*** leaning against the pyramid's faces at right angles, are no more convincing. These models pose static problems because the steep slope would have required upward leverage of the stone blocks, which was practically impossible.

Several hypotheses about pyramid building (Graefe, Landt,[26] Hölscher) share the idea that from the stepped core of the pyramids, which is archaeologically attested, it can be deduced that ***ramps*** were used which ran ***in line with the steps' lateral surfaces***, and whose slope was adjusted to the transport method chosen for the respective material. On the broad lower steps, several ramps could be installed on all sides of the pyramid, so that even the vast amount of material needed for the lower area of the pyramid could be transported and laid within an economical frame of time and effort. Keyssner suggests that stepped construction platforms were attached to the sides of the pyramid, with winches positioned on the steps to enable hauling up of the stone blocks.[27] Again, we must hold against this that the concept of layer-wise building of the core employed in this model is not corroborated by archaeological evidence.

Most hypotheses start from the assumption that traction force was employed, which is to say, bull carriages or workmen were used for hauling. If the loads were heavier than usual, or the ramp slopes steeper, larger carriages or more workmen would have been required, and also increasingly long ramps.

Some suggestions concerning the transport of building material for the pyramids are based on rather complex construction processes, so that one may wonder whether the ancient Egyptian architects would have indeed employed such sophisticated methods. What is more, the issues of constructing the top of the pyramid, setting the pyramidion, casing, and dressing often suffer neglect. The same applies to safety concerns. From all this, we cannot but draw the conclusion that yet another construction method was used which neither involved perpendicular, nor spiral ramps, nor quite so large quantities of material, nor a step construction.

My suggestion, which I shall outline in the following section, combines the idea of ramps set out parallel to the pyramid's sides and that of hauling devices with winches in connection with ramps with a steeper slope. Again, I should like to emphasize that I have incorporated only such techniques and procedures which are supported by archaeological evidence.

Ramps and Winches in the Construction of the Pyramids

Starting from archaeological evidence, I shall propose an explanation for the building of the pyramids and an estimate of the necessary time frame, using the pyramid of Menkaure as an example. I have chosen this pyramid because its stepped construction, the laying technique of inner and outer casing, and its measures are easily accessible, and therefore subject to archaeological documentation and discussion.

My hypothesis involves the assumption that construction took place ***in several phases***, which can be summarized as follows:

[23] Arnold, "Überlegungen zum Problem des Pyramidenbaus."

[24] Martin Isler, "On Pyramid Building," *JARCE* 22 (1985), 129–42, and Martin Isler, "On Pyramid Building II," *JARCE* 24 (1987), 95–112.

[25] Erhart Graefe, *Über die Determinanten des Pyramidenbaus bzw. Wie haben die Alten Ägypter die Pyramiden erbaut?* at <<*www.uni-muenster.de/Philologie/Iaek/PYR*>>.

[26] Ernst Landt, *Ein neuer Kampf um die Cheopspyramide* (Berlin, 1923).

[27] Heinrich Karl Keyssner, *Baustelle Giza. Kritische Untersuchung zum Bau der Cheopspyramide* (Karlsruhe, 2007).

1. The ***stepped core*** is built up to the sixth step. Transport of stone blocks takes place via ramps with a gradient ratio of 2:1 positioned on all four sides of the pyramid on the step platforms of the core, in line with the sides of the pyramid. These ramps are removed as soon as the core is completed.
2. Next, from the lowest course of casing upwards, a stepped structure is erected around the pyramid which serves as a ***working platform***.[28] The platform enables the workers to perform in one continuous process the laying of backing and casing blocks. Transport of stone blocks for this purpose runs via steep ramps with a gradient ratio of 2:1 positioned on the working platform which, as we have said, surrounds the pyramid on all sides.
3. After the setting of the pyramidion, the stepped surrounding structure (working platform) is ***removed***, and at the same time dressing takes place starting from the top of the pyramids, proceeding downwards.

The point of my argument is that on the one hand, the stepped core was built using steep ramps and winches, while on the other hand, a working platform was employed for the positioning of the pyramidion and the laying, working, and dressing of the casing, which was again made possible by steep ramps and winches running simultaneously on the four sides of the pyramid. Thus the complete building process including the setting of the pyramidion can be understood as one continuous process.

Winches allow even heavy loads to be hauled up over steep ramps without large towing crews. What is more, because this method combines two construction techniques that are archaeologically attested (ramps and winches), it certainly could have been available in the Old Kingdom and is therefore a likely candidate.

At first glance, it may seem contradictory to install two independent ramp systems and to remove both in the course of the building process. However, the archaeological evidence does suggest that the core was built in a distinct phase preceding the application of the casing. To quote another example, the Queens' Pyramids near the pyramid of Menkaure also consist of the core only, as the casing was not finished. In the breach at the North of the pyramid of Menkaure, we can observe that the backing stones were fitted into the outer masonry of the core. This evidence plainly excludes layer-wise simultaneous laying of core, backing and casing with the aid of one single ramp. It is probable that static concerns prompted the separate building of the core; the intention was to avoid damage to the building through earthquakes or ground shifts by combining stable outer core walls with a filling.

If the solution I have offered holds true for the pyramid of Menkaure, it is applicable to all pyramids of the Old Kingdom, with individual modifications.

In the Queens' Pyramids of Menkaure, which are also Step Pyramids, it can be observed that the heights of their single steps are roughly equal, apart from the lowest step, which is not quite as high as the others. Therefore, we may assume that in the pyramid of Menkaure, two more steps exist below the breach. The total height of these two steps is about 16.39 m, and thus not quite as high as that of the uppermost steps. This characteristic is comparable to the construction principles of the Queens' Pyramids. The reconstruction shown below (fig. 7) suggests that the core consists of seven steps. The heights of the fifth to seventh step and their batter are inferred from the measure attested for the third and fourth steps (height 8.5 m, width 4.2 m). It is also possible that the seventh step consists not of a core masonry wall with filling, but rather from well-hewn blocks that were installed in alternate courses, as can be seen at the top of the pyramid of Khufu.

[28] A working platform attached to the pyramid on all sides enables best possible access to the construction site, and safety issues are thus taken care of satisfactorily. Both are necessary concerns during the laying of the casing, notably the on-site fitting of backing and casing blocks' sides to match their finely-hewn horizontal surfaces.

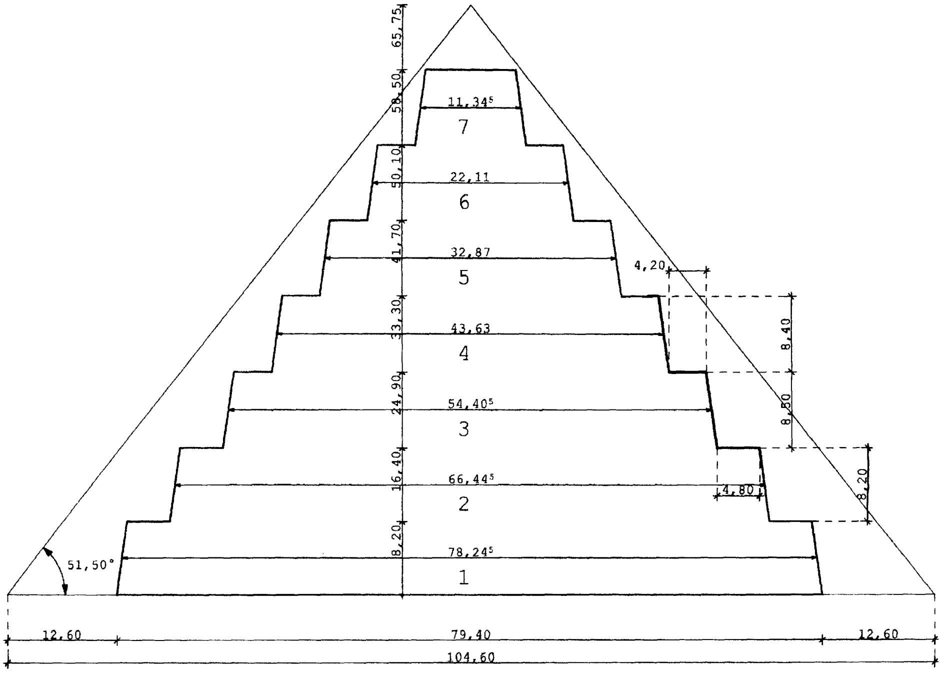

Fig. 7. Stepped core of the pyramid of Menkaure.

The Building Phases

Once a decision had been reached on the pyramid's construction, planning was completed and the site chosen. Then the building site was leveled and if at any point loose rubble raised suspicions about the static quality of the ground, these areas were supported with stone slabs. The transport ways connecting the quarries and the newly-built harbor were determined and equipped with the necessary facilities. Furthermore, the pyramid's base was fixed and aligned towards the North. The length of the base line on each side is about 80 m according to Maragioglio and Rinaldi (150 cubits?).[29] Also, the base line of the lowest layer of the casing was fixed at 196 × 200 cubits (102.2 × 104.6 m).[30] At the same time, the construction of the passages and chambers was planned, and building started.[31] As soon as these preliminary works were finished, that is, approximately a year later, the building of the actual pyramid began.

Building of the core

Archaeological evidence suggests that the second to fourth steps of the core masonry are slightly divergent in their height and width. There is no unified alignment of the steps' edges, at the best about 54°30′, but this measure does not cover all of the edges in question, for example the edge of the second step is situated further inwards. The same divergence in term of step height and width can be found in the Queens' Pyramids G III c and G III b. Thus it becomes clear that a constant slope

[29] V. Maragioglio and C. A. Rinaldi, *L'Achittetura delle Piramidi Menfite*, Band 6 (Turin, 1967) 38; (dergl. Addenda, Taf. 4, Abb. 2).

[30] Maragioglio and Rinaldi, *L'Achittetura delle Piramidi Menfite*.

[31] In the present context, it is impossible to discuss why the entrance to the antechamber was later closed, and whether this should be seen as a subsequent change of the original building plan, or whether the structure in question had been a transport pathway for granite slabs for the wainscot of the burial chamber.

could only be achieved by exact laying of backing and casing blocks. Starting from the blocks in the lowest layer of the casing, an exact batter had to be kept on the side faces as well as at the corners. In fact, this seems to be the reason for the outer angle's always being slightly smaller (51°30′) than that formed by the edges of the steps of the core masonry (54°30′). Consequently, the outer angle of inclination could be determined separate from the core, and it was not necessary for the upper edges of the steps to be positioned as precisely as the corner stones of the casing.

Right from the start of the building works, the lowest courses of blocks of the core walls were laid simultaneously at all sides of the pyramids, together with the respective filling material (stones of various sizes and shapes, gravel, tafla, sand, mortar). The stones were conveyed from one layer of blocks to the next by means of ramps which grew higher as the building increased in height. As one layer of the core walls after the other was finished, and as the respective filling was completed, the ramps were increased in height, and thus in length. However, the part of the building that had already been completed, did not require changes on the ramps. The winches however had to be moved upwards.

The transport ramps probably had a slope of 26.5°, at a ratio of base to height of 2:1, with a width to match that of the respective steps of the core (4.8 m on the first two steps, and 4.2 m on the other steps). As mentioned above, a gradient ratio of 2:1 (26°33′54″) can be observed in all passage systems of the pyramids of the Fourth Dynasty. The ramps consist of the actual transport way with a set of steps running alongside it, adding up to a total width of 3 m, which corresponds to the total width of the respective step of the core. Their design is illustrated by figure 8.

Several possibilities exist for the design of the transport way on the ramp:

1. The surface was made from smoothed limestone.
2. Ruts were engraved along the ramp surface, lined with mortar and filled with dolerite pellets. The ruts were slightly wider than the sledge runners.
3. The surface consisted of dolerite pellets embedded in mortar.
4. The surface was engraved with horizontal grooves into which wood beams were fitted.

One possible arrangement of ramps on the core steps is shown in figure 9. On the first to sixth step, ramps could be positioned on each side of the building.

The outer faces of the ramps consist of finely hewn blocks, forming a stable wall with a slight inward slope comparable to the outer shell of the core masonry. The interior of the ramps was filled with roughly hewn stones and mud bricks.

Considering the measures of the transport ramps (fig. 8), ramps can be positioned on each side of the pyramid as follows:

step 1: 2 ramps
step 2: 2 ramps
step 3: 1 ramp
step 4: 1 ramp
step 5: 1 ramp
step 6: 1 ramp

Figure 10 gives a view from above to illustrate the positioning of the ramps. The dimensions of the core steps have been added (in meters).

This serves to illustrate once more that construction works on the steps of the core may have well been carried out simultaneously on each side of the pyramid, using one or two ramps. Thus, a transport capacity emerges which is significantly higher than that of perpendicular or spiral ramps.

A perspective drawing of the ramps seem from South West is shown in figure 11.

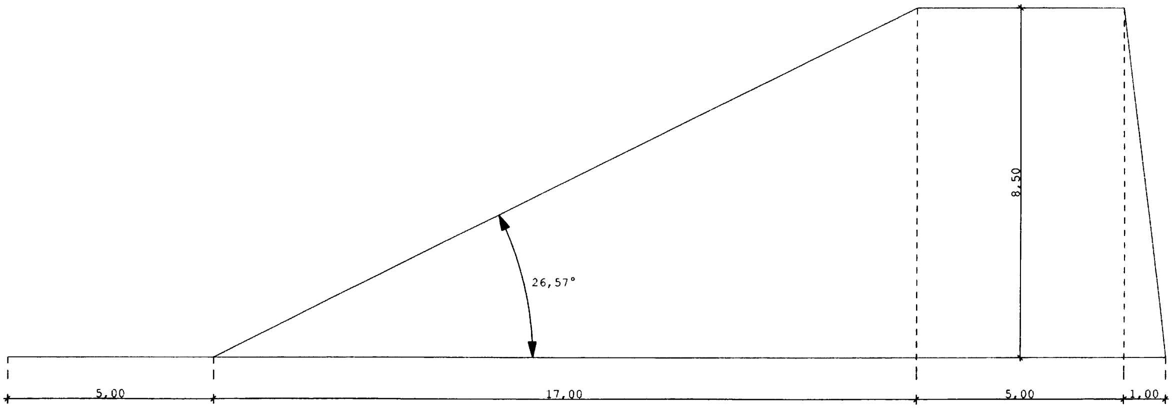

Fig. 8. Suggestion for a transport ramp.

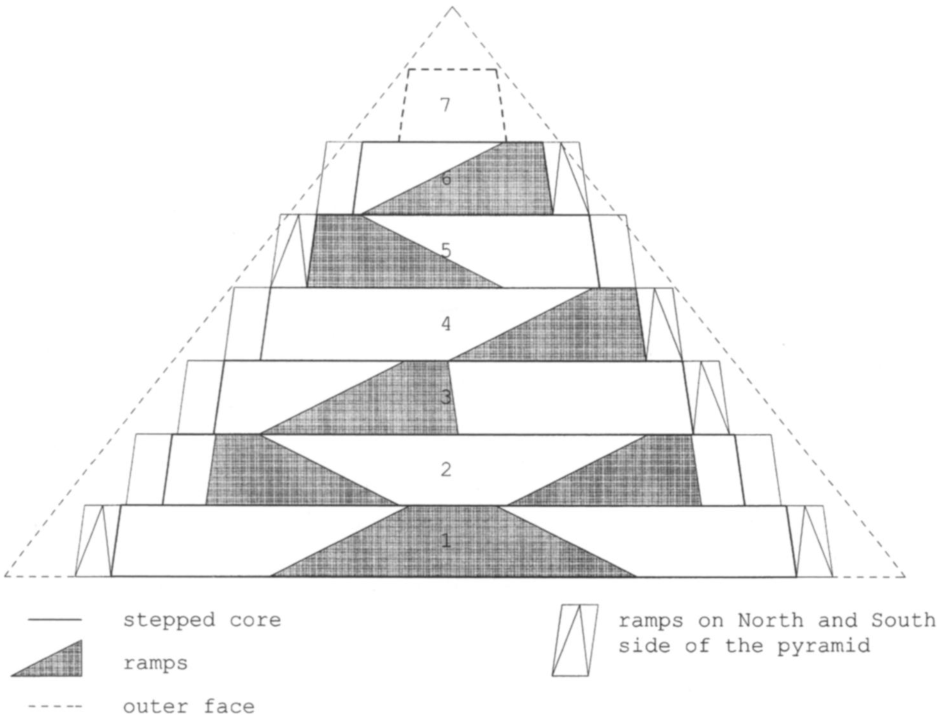

Fig. 9. Arrangement of ramps on the first to sixth core step.

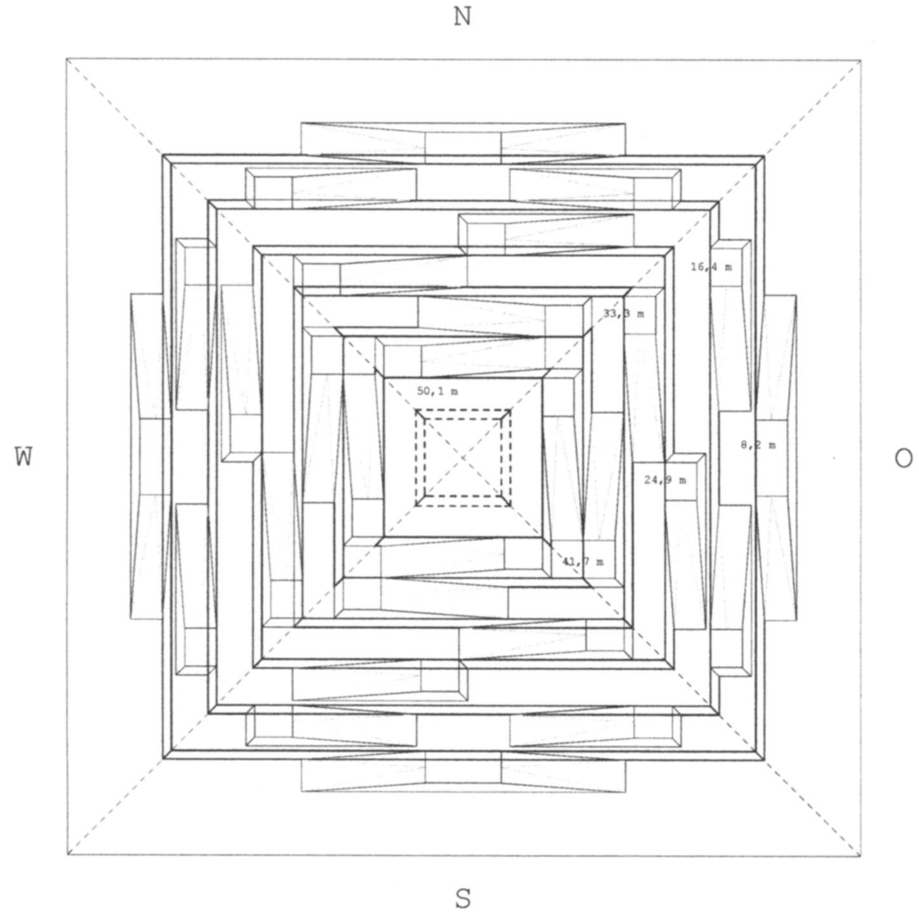

Fig. 10. All ramps on the core steps as seen from above. For the sake of greater clarity, I have used a base length of 104.6 m here, and in fig. 11.

Let us now take a closer look at the ***transport system***. We are dealing with transports on a steep ramp. I have had to adopt some common sense parameters, as there was no opportunity to confirm them by practical experiments.

On the uppermost platform of each ramp (length: 5 m), a winch is positioned at the side opposite the sloped surface. Figure 12 illustrates what these winches may have looked like.

The winch consists of wooden beams that are crossed and bound together, then firmly planted into the ground. The roller lies on top of them. The largest blocks have sizes of approximately 2.3 m × 1.4 m at a height of 0.6 m (weight 4.5 tons),[32] which means that the rollers' supports can be positioned with as much space in-between as to allow the sledge to be drawn right up onto the platform together with its load.

The front supporting beam of the roller is weighted with a maximum pressure of 3500kN (kilo-Newtons). In order to ensure that the back supporting beam is not dislodged from its bracings when it is pulled upwards towards the roller with a force of approximately 1200kN, it is fastened on the

[32] Blocks in the steps of the outer wall of the core.

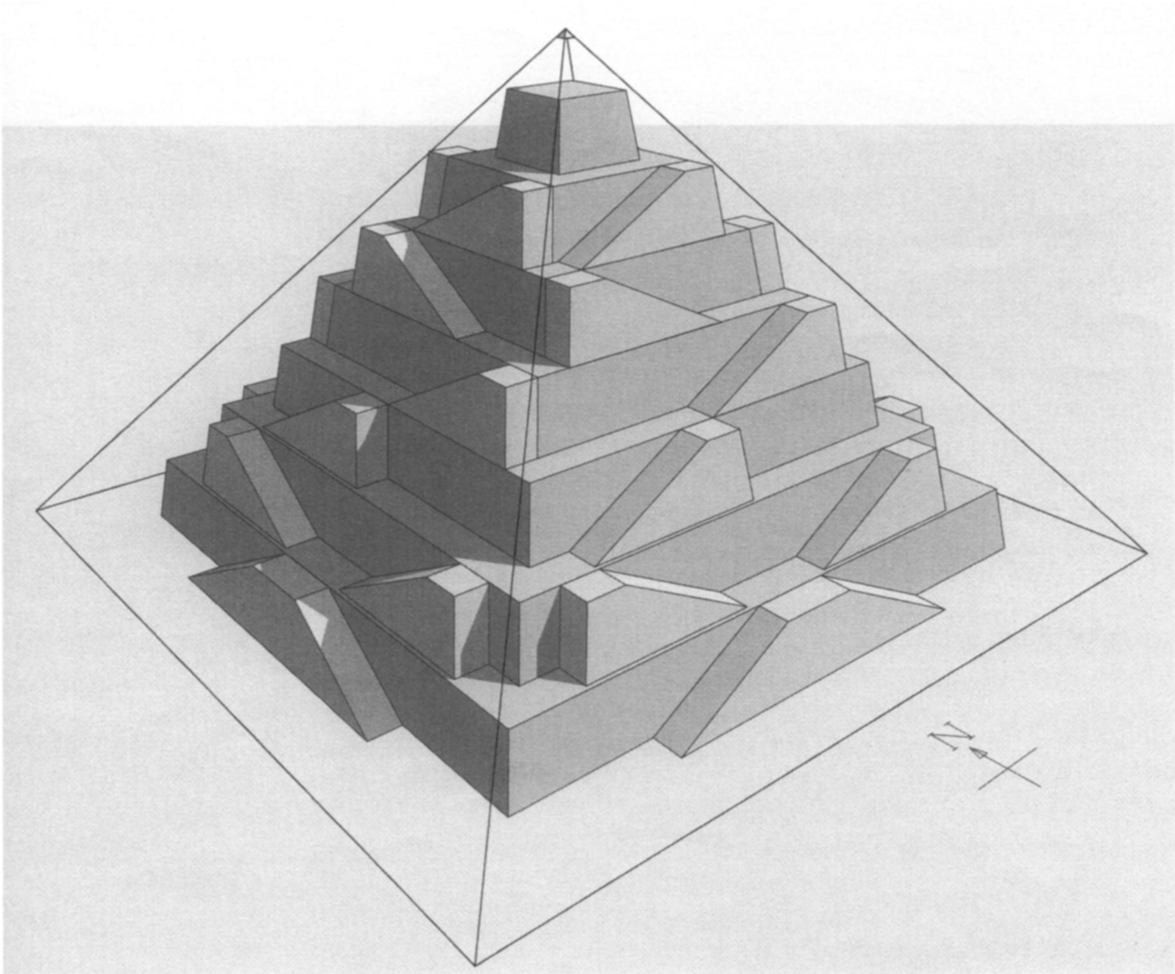

Fig. 11. Ramps used for construction of the stepped core (perspective drawing).

ramp with additional ropes. However, we have not taken into account the weight of the roller itself. Through use of hardwood and greasing of the roller's rests, the frictional force can be kept at a minimum, so that we safely may discount it.

The hauling vehicles, presumably sledges or similar devices made from wood, are likely to have measured approximately. 2.5 m (length) to 1.5 m (width). On the other hand, it is quite possible that the stones themselves were pulled up on the ramp without further supporting devices. For that purpose however, a sufficient traction force would have been needed. The advantage of this method would have been that the time consuming tasks of loading and unloading of the stone blocks, and also the transport of the sledges back down, were not needed. In any case, the hauling devices must be designed in such a way as to ensure that they can be pulled in both directions (change of direction at the top of one ramp to be pulled towards the base of another).

To estimate the maximum necessary traction force for transport of the heaviest supposed load of 4.5 tons (see above), we base our argument on the following assumptions: one block measured approximately 2.3 m × 1.4 m × 0.6 m. Several ropes were fastened to it, which were then led through a winch

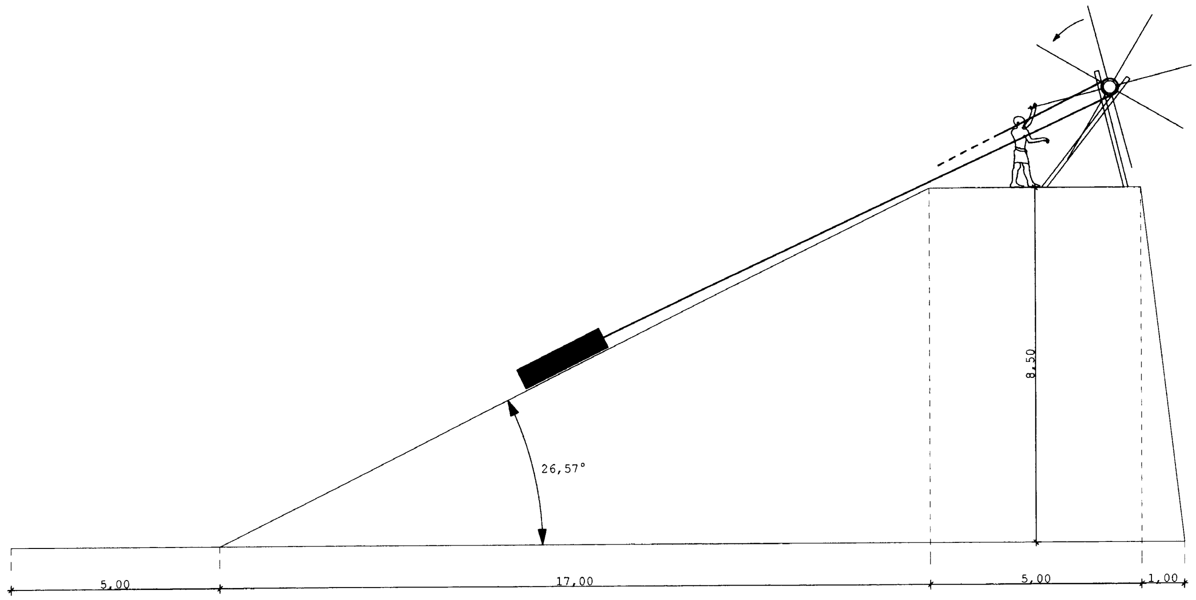

Fig. 12. Design of the winch at the top end of the ramp.

with 0.3 m roller diameter, coiled several times, and safely lodged to avoid slippage. On either side of the winch there were eight or more spokes with an average length of 2 m, on whose end a rod was fastened horizontally, or else the spokes were connected with wooden struts. The power transmission amounts to 0.15 m (roller radius) per 2 m spoke length, that is to say 1:13. Four men can work on each spoke with a force of 30 kp (kiloponds) (force directed downwards or forwards), moving 120 kp × 13 = 1560 kp. If there are two spoke levels altogether, one on either end of the winch, a total traction force of 3100 kp is available.

This is the traction force necessary for transport of a stone block over a smoothed limestone ramp with a gradient ratio of 2:1 or with a slope of 26.5°, and a friction of 0.25, that is to say the force needed in the *least favorable circumstances*. Supposing that sledges or other wood devices with less friction were used, or horizontally embedded wood beams,[33] fine sand strewn over the sloped ground,[34] or another kind of support covered with dolerite pellets, a traction load of a mere 2200 kp has to be achieved,[35] which may be further lowered when smaller blocks are moved.

Then again, friction is necessary to ensure that the roller does not spin freely under the coiled rope. This is guaranteed by the use of a roughened wood surface, the natural roughness of the ropes, several coilings of the rope, and a traction force along the ramp down to its base. The rope is led back to the base of the ramp, where the workmen ensure that it is always pulled tight. At the same point, a safety device would have prevented the load from slipping if, for example, a spoke snapped; that is to say, a stopper (wood post firmly lodged in the rock) could hold the rope when it was in danger of snapping back.

[33] This technique is archaeologically attested only from the Middle Kingdom onwards, but then again, the principle of the roller is known already from the Old Kingdom.

[34] The favorable effect of fine sand is comparable to the lowering of rolling friction by means of stone pellets.

[35] As I am only aiming at a rough outline at present, I have not taken into account the minimal friction caused by the roller's rests.

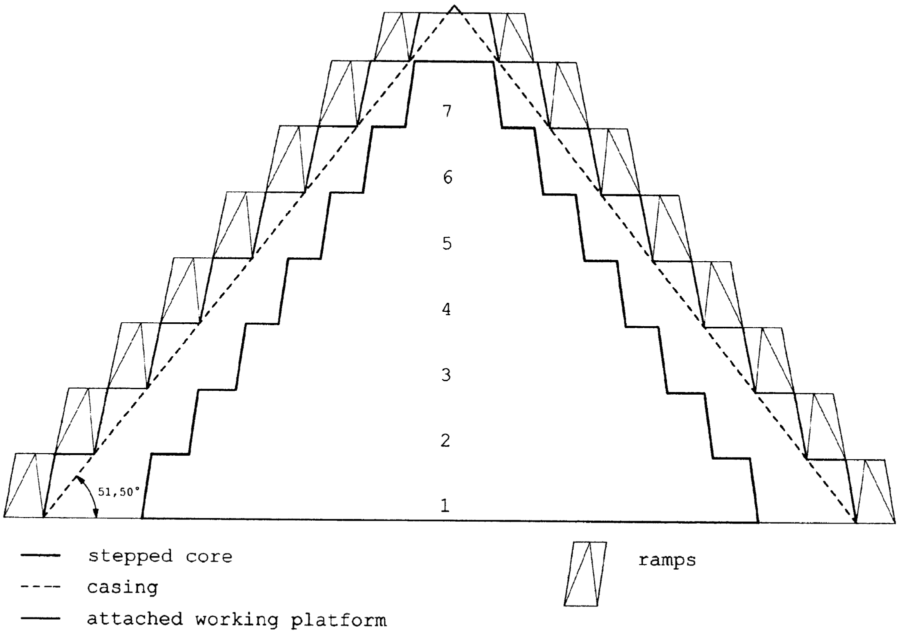

Fig. 13. Working platforms attached to the faces of the pyramid of Menkaure.

Horizontal transport of a block on either end of the ramp towards its definite position in core or casing, or towards the starting point of its transport to the next level, would be carried out by means of levers or stone pellets. As in the pyramid G III c (Menkaure), layers are also visible in the core filling. It is therefore quite possible that the blocks were moved across a surface covered with loose stone pellets. Furthermore, we have reason to assume that the uppermost horizontal layer of the ramps was covered with dolerite pellets on the first few meters after the ending of the slope, in order to allow the sledges or the blocks to be rotated if necessary, and to await further transport as they were sitting on a bed of stone pellets.

Application of the backing blocks

In many pyramids it is still obvious today that measuring and laying of the base course of the casing was carried out most meticulously. This supports the assumption that the backing blocks[36] and the casing[37] were completed starting from the base of the pyramid as a rule.[38]

In some pyramids, like the Queens' Pyramids of Menkaure G III b and G III c, only the core was finished.[39] I should like to put particular emphasis on this fact at is rules out virtually any other model than that involving separate construction phases for core and casing.

Exact laying and working of backing and casing blocks requires a platform surrounding the pyramid, for no other solution ensures the safety of the workplaces. In figure 13, I have sketched a solu-

[36] By backing, or backing blocks, I mean the horizontal layers of stone blocks between the steps of the core and the casing, which consists of Tura limestone and Assuan granite.

[37] The blocks of the casing from Tura limestone or Assuan granite were left in boss at the stage of fitting the casing, to be dressed later.

[38] Stadelmann has noted that in the Bent Pyramid, the casing was laid right at the beginning, together with the core. In that case it was laid starting from the base, moving towards the top (Stadelmann, *Die ägyptischen Pyramiden*, 226).

[39] Peter Jánosi, *Die Pyramidenanlagen der Königinnen* (Wien, 1996), 85.

tion involving working platforms attached to the pyramid's sides. Ramps would have been erected on these platforms to match those suggested with reference to the core construction phase (see above).

As can be seen in the breach on the North side, the core steps were filled out with backing stones to match the respective batter. This process is technically impossible without an attached working platform. The same is true for laying and working the stones of the casing. Only an attached working platform enables the workmen to fit the blocks quite so neatly into the given spaces. Also, this model explains how the pyramid's surface could be dressed top down during removal of the attached working platforms. Up until then, these blocks would not only have been as yet unsmoothed, but also parts of them would have protruded from the pyramid's walls. Their rough surfaces would have ensured safe lodging of the ramps leaning onto the pyramid with blocks resting on the surface of the pyramid's outermost masonry. As the ramps are built layer by layer, the ramp blocks facing the pyramid are safely positioned in this manner, lending sufficient security to the ramps walls.

For the transport of blocks on the respective steps of the platform, I would suggest ramps with a width of approximately 5 m, similar to the core ramps, made from mud bricks or smaller stones, with outer flanks made up from stone walls. These brick ramps display a gradient ratio of 2:1, and they grow with the platform from layer to layer.

Within one layer, first the backing is completed and then the casing is laid, each new course of casing blocks on top of the previous one. The working platform may well have served for the construction of the seventh step of the core also (if indeed there was one), and of course for the setting of the pyramidion.

The blocks of the casing were worked with remarkable precision even before transport on their horizontal faces. Their fronts, however, were left undressed. The sides of these blocks were often cut very finely, partly during laying. As can be seen in several instances, some of the cutting was not executed vertically, but rather to fit the situation found on-site. This kind of work requires a platform attached to the pyramid's face, because only then, the required sawing on both sides would have been possible in safe circumstances. Only very closely fitted casing blocks could prevent leakage of water and sand into the masonry, thus offering protection from damage through erosion. Before a casing block was fitted, the slope of the pyramid was sketched on the previous block so that later, dressing could start from this mark in keeping with the exact slope. Dressing of the outer faces of the casing blocks previously left in boss, starting at the top of the pyramid and proceeding downwards as the platform was removed, was feasible because the brick ramps were dismantled when work at the top had been completed.[40] To illustrate how the stone surfaces were smoothened, see figure 14 with a representation from the tomb of Rekhmire (TT 100, Thebes West).[41]

By measuring the length of the sides of a finished course of casing blocks at the pyramid stump from one corner stone to the other, it was possible to ensure that the angle of inclination of the corners and the batter of the side faces of the pyramid still followed the designed course. Exact measuring of the base of the pyramid of Khufu has proven that this kind of measuring posed no insurmountable difficulties, in spite of the rock spur enclosed by the pyramid, which prevented diagonal measuring.

[40] Herodotus reports that the pyramid was finished top down (Herodotus, *Historiae* II.125, translated by Alfred Horneffer, *Herodot Historien. Deutsche Gesamtausgabe* [Stuttgart, 1961]). According to Diodorus, the construction of the pyramids involved earth walls (mud bricks) along the outer face of the pyramids (Wilhelm von Bissing, *Der Bericht des Diodor über die Pyramiden* [Berlin, 1901])). Pliny mentions a terrace system (Goyon, *Die Cheopspyramide*, 173).

[41] Norman de Gavis Davies, *Rekh-mi-Re*, PMMA 11 (New York, 1943), pl. 62.

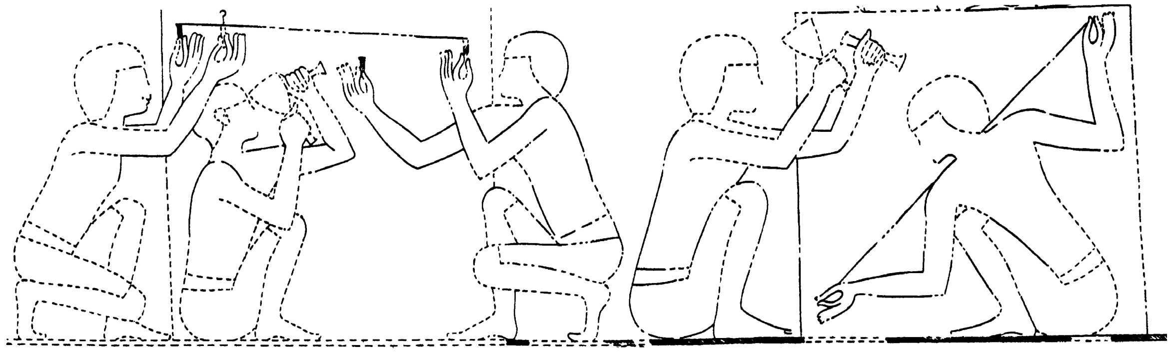

Fig. 14. Smoothing of stone surfaces, representation from the tomb of Rekhmire (drawing after Davies, Rekh-mi-Re, pl. 62).

Calculating the Building Time of the Pyramid of Menkaure

In calculating the efforts made in building the pyramid for Menkaure, and the resulting building time, we must use rough estimates in some points, especially as far as the block sizes are concerned, which are different in each layer. However, as the burial chambers of the pyramid of Menkaure are located below the core steps, estimating these numbers is comparatively straightforward.

The measures of core and backing blocks are approximately 1.3 m × 1.3 m × 0.7 m (1.2 m^3), thus their weight amounts to approximately 3 tons, as the specific weight of limestone is 2.4 tons per m^3.[42] This calculation accounts for the fact that the core stones have slightly smaller dimensions than those of the outer walls of the core. These numbers serve the purpose of transparent reckoning, as the average block size will be used in the calculations of sledge loads and towing below.

For the stones of the casing, the mean measure is 0.7 m × 0.7 m × 1.1 m (0.54 m^3, approximately 1.5 tons). Two of these blocks would form a sledge or hauling load.

Transport efforts as calculated here account for the building itself with core and casing, as well as the attached working platform. Moving of the winches would only become necessary occasionally, depending on the number of transport units. Therefore, I have excluded this task from my calculations.

Also, the flat rate stone volume assumed for spaces filled with mortar, sand, and so forth, is negligible.

Throughout the construction process, a broad range of transport and building tasks was employed. After upward transport, the stones had to be moved horizontally into their definite position. Due to the limited number of ramps, upward transport required far more time than horizontal transport within one layer, as a greater number of workmen could be set to the latter task simultaneously. Horizontal transport may therefore be regarded as comparatively irrelevant to the building schedule, compared to ramp-dependent transport. Consequently, I have only taken into account ramp-dependent transport.

My model of transport of a sledge load, or a hauling process, up to a height of one step, is based on the following practice-based assumptions: the duration of transport up to the next step amounts to approximately 5 minutes, that is a towing speed of approximately 5 meters per minute, amounting to five winch turns per minute. For fastening and releasing of the ropes from the sledge or the block, the shifting of the sledge or respectively the load, and the back transport of the empty vehicle, rope and so forth, 10 minutes should suffice. Therefore, a unit duration of 15 minutes is realistic.

[42] Dieter Arnold, "Kalkstein," *Lexikon der ägyptischen Baukunst* (Düsseldorf, 1997), 119.

Further to the schedule calculation, we need to keep in mind that the blocks for the upper steps had to be moved over several ramps, which was a more time-consuming procedure. On the other hand, if we start from the assumption that a block was conveyed continuously from one ramp to the next to its final destination, it follows that a new block would reach the construction level every 15 minutes, be it via sledge or hauling. The additional effort necessitated by the greater height that had to be overcome could be compensated by an increased workforce. The assumed average values for block weight and unit duration directly influence the estimated building time. If these sizes are altered, a new schedule will result. Obviously, calculations such as these are always more or less hypothetical, depending on the numbers inserted above.

The respective volumes of the six core steps add up to a volume of 140,736 m^3, that is 117,280 stone blocks at a volume of 1.2 m^3 each and an equivalent number of sledge loads. The seventh step with its volume of 900 m^3 was built at a later stage when the platform had been installed (see above). Further to a calculation of the building time of the core, we propose that a sufficient workforce was available on three hundred days of the year, ten hours per day (shift work), which means that under the circumstances outlined above (15 minutes per load), a total of 12,000 units were conveyed in a year. Therefore, the building of the core took 1.7 years. We still have to add construction and removal of the ramps on the first to sixth step, that is thirty ramps at a total volume of approximately 9000 m^3, requiring a total of 0.4 years, if work took place on all sides of the pyramid. Therefore the entire ***core*** could have been readily completed in just ***2.1 years***.

My calculation of transport volume and building schedule for the ***working platform*** attached to the outside, plus the seventh core step, backing and casing, covers a volume of 157 728 m^3 or 17,486 work units. If again we base our calculations on the availability of the workforce as outlined above, a total ***1.5 years*** results. Next, the ramps and the platform need to be removed, and the stones left in boss need to be dressed. The ***removal*** of said structures requires ***0.5 years*** in keeping with the framework set out above.

Only a rough estimate can be offered for the ***dressing works on the facade***. A time frame of about ***0.5 years*** seems realistic in the light of the following considerations. Firstly, the lowest sixteen layers were left partly unfinished (granite wainscot). Secondly, we may assume that on one day (10 hours of work in shifts) one team of workmen succeeded in dressing a facade area of 1.0 m × 1.0 m (Tura limestone from the seventeenth layer onwards). In the case of the granite wainscot, the area would have only been 0.5 m × 0.5 m.

Then, in order to calculate the schedule for the dressing works, the outer face of the pyramid is divided into eight stumps (arranged in steps as in figure 13, for measures see figure 7). Next, the circumference of each is measured and the respective area is calculated. Thus, the number of days spent on the task can be determined. In order to avoid intruding on one another's workspace, there is a minimum distance between two work teams amounting to 1 m. From this, there results the number of teams set to work on each pyramid stump and the number of days needed for dressing. By employing up to 170 teams, the same work process can be undertaken in the lower part of the pyramid, on all four sides at the same time. The number of teams can be increased steadily, and new teams can be trained and broken in continually. At a height of 65 m, excluding the eight lowest layers, an approximate duration of 155 days or 0.5 years results. However, we must still keep in mind that the removal of the working platform and the ramps must be coordinated with the dressing and disruptions must be dealt with. To account for such unforeseeable circumstances, another ***0.5 years*** are added.

The debris accumulated during removal of the ramps and the working platform, largely mud bricks, amounted to roughly 60,000 m^3, that is approximately 25% of the pyramid's volume. While mud bricks could be distributed for use on the surrounding agricultural domains, the rest of the debris was stored on the north eastern slopes of the desert plateau and in the area towards the south of the Giza plateau.

The ***building of the pyramid of Menkaure***, not counting the time spent on pre-construction preparations, therefore took ***approximately 4.6 years***. All in all, an average volume of 202 m^3 of stone or 186 blocks were moved per day.

Towards a Comparison of the Building Times of the Red Pyramid and the Pyramid of Khufu

How does the schedule proposed for the pyramid of Menkaure compare to that of the other pyramids? In the following section, I propose for comparison some calculations for two other pyramids, for which a good enough time frame is widely acknowledged. Again, my calculations are based on estimates in some instances. I base my arguments on the points made above with reference to the core steps, ramps, and unit duration. Similarly, the construction of backing, casing, and working platform is assumed to follow the same principle as illustrated above.

Building time calculation for the Red Pyramid

In order to estimate the building time for the Red Pyramid, we need to first establish a framework of data that can only partly be verified by archaeological evidence due to the pyramid's state of preservation.

The height of the respective steps is assumed to be 10 m. Therefore, the pyramid has a total of ten steps.

The average size of the backing and core blocks is approximately 1.1 m × 1.0 m × 0.7 m,[43] which is a volume of 0.77 m^3, or a weight of 1.9 tons.

Although the ramps are slightly longer, the duration of a single unit can be fixed at 15 minutes, because the average weight is lower in the Red Pyramid than in the one previously discussed.

The number of working days per year and hours per day is equal to that discussed above.

The building of the two burial chambers is not taken into account, as these are subterraneous structures.

These assumptions are illustrated by a cross-section of the Red Pyramid which reveals the stepped structure of the core (figure 15).

Our estimation of the building schedule of the Red Pyramid, not counting the preliminary preparations, will again start from the assumption that construction works took place on three hundred days of the year, on ten hours of each day, in shift work. It follows that a total of 12,000 transport units of 15 minutes each could be carried out per year. Thus, ***the construction of the core*** of the Red Pyramid took ***9.9 years***. The time needed for the construction of the working platform, backing and casing, adds up to ***4.8 years***. For subsequent removal of ramps and platform, and dressing of the

[43] John F. Perring, *Pyramids*, vol. 1 (London, 1893), has measured the height of twenty-one steps of backing blocks starting from the bottom step. In total, their height is 21.4 m, which leads to an average step height of 1.02 m. The width is said to be 0.9 m. V. Maragioglio and C. A. Rinaldi, *L'Architettura delle Pyramidi Menfite*, vol. 3 (Turin, 1963), 126, and also *Addenda*, pl. 19, fig. 6, suggest the heights of the stones are 0.5 to 0.7 m and their depth 0.9 to 1.2 m. Ranier Stadelmann, "Die Pyramiden des Snofru in Dahschur. Erster Bericht über die Ausgrabungen an der nördlichen Steinpyramide," *MDAIK* 38 (1982), 380–81, writes that the height of the corner blocks of the backing, up to a point at two thirds of the height of the pyramid, was 1 to 1.3 m. Richard Lepsius, *LD* 1, texts (Berlin, 1897), 206, describes the blocks of the core masonry to be altogether ". . . maybe not quite as large as in Giza. . . ."

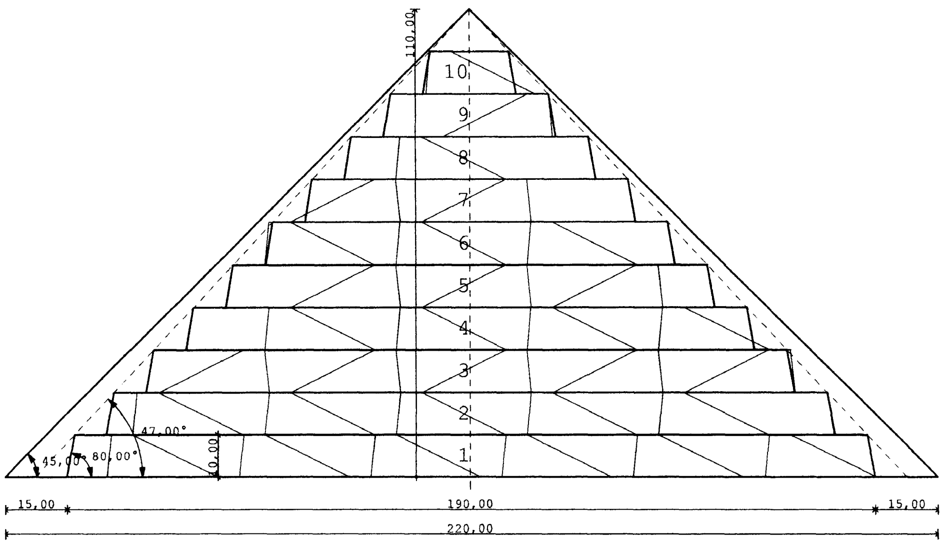

Fig. 15. Arrangement of ramps for the construction of the core of the Red Pyramid.

blocks left in boss, ***1.7 years*** should suffice. The time frame for dressing comprises approximately 223 work days or 0.75 years. If we assume that this time must be added to that needed for the removal of the working platform and so forth, the actual **building time of the Red Pyramid** results at **16.9 years**, during which in total an average of 443 m^3 of stone, or 576 blocks, were moved each day.

Building time calculation for the pyramid of Khufu

Again, as in the case of the Red Pyramid, some assumptions have to be made with reference to the measurements and the number of the core steps that are partly impossible to corroborate by archaeological evidence as yet.

My starting point are my own observations and studies. In the tomb-robbers' tunnel the structure of the core masonry changes abruptly in layer seven (lower edge at 7.06 m over foundation level), about 15 m behind the entrance. Considering the horizontal measures of the outer wall of the first core step (1 m) and of the casing which is not preserved (approx. 3 m), and also the inclination of the outer wall of the core steps (80°), there results a base length of the first step of the core of approximately 197 m (375 cubits).[44]

The height of the steps is likely to be 11 m and the number of steps twelve.[45]

The width of the steps accordingly is 5.75 m, if we take into account the alignment of 54°30′ along the steps' edges on the lateral surface.

The unit frequency differs the pyramid of Menkaure, because the ramps are significantly longer, thus approximately 20 minutes.

[44] This is an assumption based on calculation, which does not include the streaks of solid rock that reach the backing. The same is true for the suggested ramp arrangement on the first step of the core.

[45] Graefe, *Determinanten*, proposes eleven steps at a height of 13 m each for the core steps, at a width of 7.35 m. Thus, the line of the steps' edges on the lateral surface also reaches 54.5.

The volume of the bed rock core in the base of the pyramid is assumed to amount to 7.9% by Haase,[46] and 7.7% in more recent studies, i.e., 200,000 m^3.[47] Goyon supposes a volume of 127,000 to 160,000 m^3.[48] I shall use the volume of the rock core given by Haase.

Further construction data as the number of working days per year and the size and average weight of the stone blocks and so forth are the same as for the pyramid of Menkaure.[49]

To illustrate these suggestions, figure 15 shows the pyramid of Khufu with its stepped core.

In order to estimate the building time of the pyramid of Khufu, not counting the preliminary preparations, we again assume that a sufficient workforce was available on three hundred days of the year, ten hours a day, in shift work, so that at a duration of each transport unit of 20 minutes a total of 9000 rounds per year could be achieved. Accordingly, for the ***core*** of the pyramid of Khufu, the time needed for transport of blocks amounts to 13.1 years, or just ***12.4 years*** if we subtract the volume of the bedrock core. The building time for the working platform, backing and casing amounts to a total of ***6.0 years***. Finally, the ramps and the platforms need to be removed, and the blocks left in boss require dressing, which all in all takes ***1.8 years***. As the time spent on dressing amounts to approximately 286 work days, or ***one year***. If we assume that this must be added to the removal of the working platform and so forth, the actual ***building time of the pyramid of Khufu*** results in ***21.2 years***, during which an average amount of 393 m^3, or 327 blocks per day were moved.

I should like to emphasize again that these observations are based on rough estimates for the block sizes and weights, and to be precise, they ought to be modified by adding some more detailed explanations, for example as to how the large limestone blocks over the entrance on the North side of the pyramid, or the granite blocks of various shapes (Grand Gallery, burial chambers, stress-relieving chambers, plugging blocks) were moved (figure 16).

It may well be the case that in the lower area at the various pyramids' East some tangential ramps with a less steep inclination were erected in order to convey the larger blocks with a weight of up to 60 tons, which were delivered along the causeway. On the other hand, it is quite possible that the causeway was continued at an even inclination (10:1) towards the base of the pyramid or into the actual building site, reaching a height of 40 to 45 m above base level, at which height the ceiling slabs could be conveyed further upwards. These considerations, however, are best discussed elsewhere.

Starting from his own observations on the topographical situation at the SW corner, Lehner shows that the ramp, approaching the pyramid from the Southern Quarry, would have met the pyramid at about 30 m above base level.[50] Furthermore, we should not go without mentioning a solution for heavy load transports during the building of the pyramid of Khufu which Haase has published recently.[51]

Summary of Results

Several solutions that have so far been offered for issues of the construction of the ancient Egyptian pyramids by Stadelmann, Arnold, Lehner, Goyon, Klemm and Klemm, Lattermann and Houdin,

[46] Michael Haase, "Der Felskern der Cheopspyramide," *Zeitschrift für Archäologie und archäologische Grenzwissenschaften* (1/1993), 5–13.

[47] Michael Haase, *Eine Stätte für die Ewigkeit. Der Pyramidenkomplex des Cheops* (Mainz, 2004), 17.

[48] Goyon, *Die Cheopspyramide*, 117.

[49] In a number of publications, an average volume of $1m^3$ is assumed for each stone block, from which an hypothetical volume of the pyramid of 2.3×10^6 m^3 results. The solid rock core, cavities, and the spaces filled with mortar and rubble are neglected.

[50] Lehner, "Development," 109–43.

[51] Michael Haase, "Eine Rampe für Schwertransporte beim Bau der Cheops-Pyramide," *Sokar* 15 (2/2007), 48–49.

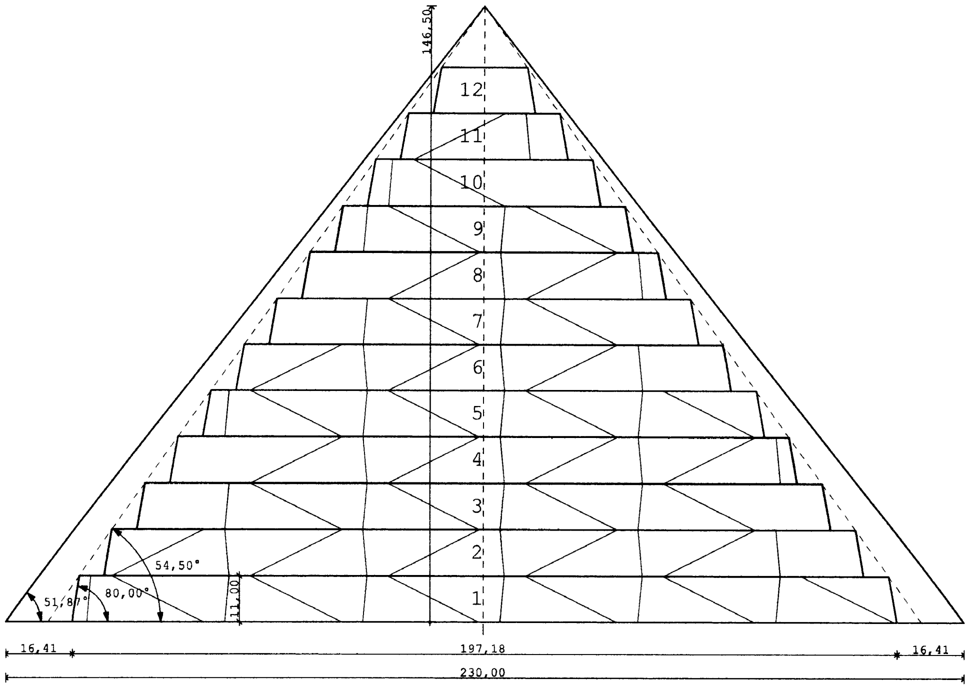

Fig. 16. Arrangement of ramps for the building of the core of the pyramid of Khufu.

which are based on the assumption that perpendicular or integrated ramps were used. Other explanations involve steep ramps running parallel to the core steps (Landt, Graefe) have also been noted. Still other authors suggest the use of winches, for example Riedl, Pitlik, and Keyssner. However, most of these authors assume that the core was built layer-wise; moreover, many do not offer solutions as to how the pyramidion was set, and how safety was ensured when the casing was applied and dressed. Building time calculations are only offered occasionally.

The observations which I have presented here and elsewhere, lead to the conclusion that difficulties encountered in building the Bent Pyramid prompted the architects of the Red Pyramid to revise their construction methods in order to control the threat to the pyramid through ground erosion and earthquakes. At the same time, it was crucial to keep the building time as short as possible to meet the king's request for swift completion. As a result, a stepped core was erected, to offer more stability on the one hand, and on the other hand to enable ramps to be positioned on all four sides of the pyramid parallel to the core steps, in order to allow for material transports in a shorter time frame. Also, larger stone blocks were used. Subsequently, during the building of the pyramid of Khufu, the same methods were employed, and the size of the blocks was increased still further, in order to finish the vast building as soon as possible.

My hypothesis for the building of the Step Pyramids of the Old Kingdom involves combined use of ramps and rollers, which are both archeologically attested, in a device commonly known as winch. Compared to previous suggestions involving transport of material by towing crews, the ramps were positioned in line with the steps of the core and to the working platform and were thus built with a steeper slope. As we have seen in the case of the pyramid of Menkaure, there is no longer a need for perpendicular ramps, or integrated ramps with less slope. Under these circumstances, we may dispense with any more complex solutions for the constructions. The use of several ramps with a steeper gradient ratio (26.5°, 2:1) on the core steps and the platform, on each side of the pyramid, leads to a steady and frequent influx of material, thus emerging as the best time-saving device that has been proposed so far.

Following the construction of the core and the removal of the respective ramps, backing and casing were applied layer-wise, after stepped working platforms with ramps had been installed around the pyramid, all of which were removed as the dressing of the casing proceeded top down. This same platform also offers a convenient solution for works at the pyramid's top including the pyramidion.

The calculations of the transport effort and the resulting building time are based on the least favorable circumstances in terms of block size and weight, the ramp surface's friction, and transport unit duration. If any of these conditions are found to be more favorable, either the number of ramps could be reduced, or the building could be finished sooner. I have occasionally mentioned alternative solutions to some details, such as the ramp surfaces, but these do not have a significant effect on the overall construction method.

A calculation for the building times of the pyramids of Menkaure, Seneferu (Red Pyramid), and Khufu would realistically render the following results:

Pyramid of Menkaure:
- planning and preparation—1 year
- building time, including dressing—approximately 4.6 years[52]
- total ***5.6 years.***

Red Pyramid:
- planning and preparation—2 years
- building time, including dressing—approximately 16.9 years
- total ***18.9 years.***

Pyramid of Khufu:
- planning and preparation—2 years
- building time, including dressing—approx. 21.2 years
- total ***23.2 years.***

These building times fit well within the accepted dating of the reign of Seneferu (thirty-five years),[53] Khufu (twenty-three years),[54] and Menkaure (twenty-eight,[55] or six,[56] years).

The present article offers a solution that has been developed from archaeological evidence.[57] It is centered around the idea of "pyramid building with ramps and winches." The solution involves steep ramps positioned in line with the steps of the pyramid's core, equipped with rollers in the form of winches for transport, and superseded by a working platform attached to the pyramid's sides to enable safe setting of the pyramidion and dressing of the casing.

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[52] The dressing of the casing is not quite finished.

[53] According to new results, thirty-three years, Rolf Krauss and David A. Warburton, *Ancient Egyptian Chronology* (Leiden, 2006), 490. The building of the Red Pyramid was begun in year fifteen of the reign of Seneferu.

[54] According to new results, twenty-six years, Krauss and Warburton, *Chronology*, 491.

[55] Jürgen von Beckerath, *Chronologie des pharaonischen Ägypten* (Mainz, 1997), 188.

[56] According to new results, only six years, Krauss and Warburton, *Chronology*, 485.

[57] Frank Müller-Römer, *Pyramidenbau im Alten Ägypten* (München, 2008), published electronically at http://archiv.ub.uni-heidelberg.de/propylaeumdok/volltexte/2009/349.