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The Building of the Pyramids: Reconstruction of the Ramps

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Review

The seven great pyramids of Giza, Dahshûr, Saqqâra and Meydûm amaze and fascinate not only their visitors, and did so for almost five thousand years. They employ imagination as well as science and pose many mysteries to both, always and still. One of the still largely unresolved questions in Egyptian archeology is that of the methods that made it possible to build the grandiose funerary pyramids of the 4th and 5th dynasties. Although new and ever more precise findings are constantly expanding the state of knowledge, there is still no recognized line of reconstruction of the building processes. Consequently, the study presented here approaches the solution from several different perspectives.

Not all, but many aspects of the pyramid construction sites are of a purely pragmatic nature: the technical parameters of the buildings and the concrete topography are clearly comprehensible. A given building mass in the given geometry was undoubtedly successfully completed using the means available according to archeological knowledge at the time of construction; the mere appearance proves that. The available construction time was determined by the life and reign of the respective kings - here there are still uncertainties, but the dates discussed in the literature can be narrowed down approximately.

The question of how the required mass of stone was transported to the enormous construction height of up to 146.6 m in the given construction time has remained a mystery to this day. There are certain numerous hypotheses, the number of which continues to grow. So far, however, no hypothesis has found widespread agreement among experts.

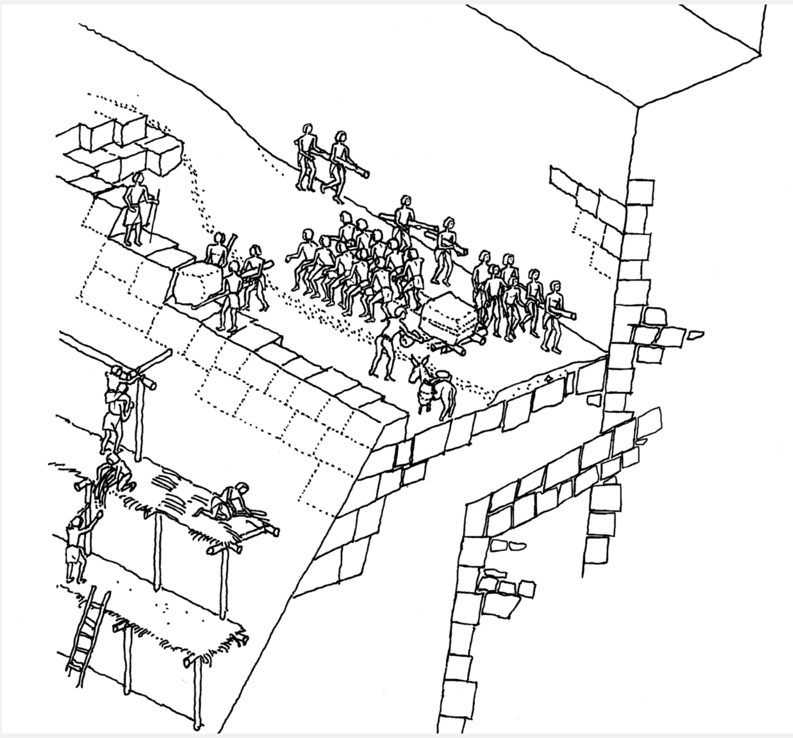

Figure 1: Section of the pyramid construction site E2 in Meydûm.

In order to be able to authentically understand these processes, it is by no means sufficient to limit oneself to the purely technical data of the construction sites. Comparisons and observations from the cultural, regional and historical context are also indispensable indicators, even if their interpretation often depends on intuition and not on scientific measurement data alone. While the paradigms of geometry and gravity are as valid today as they were in Khufu´ times, cultural practices were embedded in the temporal and regional context of religion, social organization, economy and other aspects of early Egyptian civilization (Figure 1).

That seems to me to be the Gordian knot in the problem: looking at the cultural context does not have to be seen as an obstacle to the technical understanding of the pyramid construction sites, but as an invaluable help. It wasn´t like that (and here the modern engineering view is more harmful than helpful) that Egyptians were faced with the problem of building huge pyramids, which they then somehow had to solve. It´s the other way around: they did what their social system, their religion, their economy told them to do, and this resulted in pyramids.

The workers who made it all possible were mostly simple people with natural needs. Within the limits of the world into which they were born, they tried their best to do everything right as far as they could – of course also by following the orders of their elites. The reconstruction of the pyramid construction should primarily understand the builders and workers and their actions. Basically it is them, as an example for mankind, who became immortal through the pyramids.

For all topics, I fall back on observations and references that are widely recognized in the literature. In addition, I bring in many years of experience in construction management in the traditional construction industry of the clay-built town of Shibâm, where ancient oriental building methods have been preserved to this day, which has intensively supplemented my studies in architecture of the ancient orient.

The later pyramids were mostly built of mudbrick, others in a different shape or inclination. The later buildings therefore allow only limited conclusions to be drawn about the construction processes of early pyramids. This justifies concentrating the considerations of construction processes on the early great pyramids. In the course of the classic pyramid building program, three phases can be roughly distinguished in the design. In the beginning there were the step pyramids in the so-called shell construction in which the steps were carried out as a kind of inner retaining wall up to the base line[1]. These included the Pyramid of Djoser and the Pyramid of Sekhemkhet at Saqqâra and of Khaba at Zâwiyat el-´Aryân (a little to the north). The construction in Meydûm was also started as a step pyramid in shell construction, in two construction phases.

The two Snofru pyramids in Dahshûr and the last construction phase of Meydûm mark the turn to a largely uniform construction method in horizontal stone layers[2] as well as to the „true" pyramid shape. Their mature form and perfection was eventually achieved in the two giant pyramids of Giza, the greatest structures of antiquity and the only surviving ancient „wonder of the world".

A third type was built again using an inner step pyramid, but now without the original system of inner shells[3]. This includes the Menkaurê pyramid, but also the queen pyramids of Khufu, where the stepped masonry is exposed today. However, later pyramids such as those of Sahurê in Abu Sîr from the 5th dynasty[4], and pyramids of the 8th dynasty are also reconstructed with an inner step pyramid[5].

During the development of pyramid building, the step construction with inner shells must have been decisive for the conception of the construction processes. The basic construction principles of pyramid construction are mostly sought in Giza. Yet most essential determinants of the construction process must have been developed during the construction of the step pyramids in Saqqâra and Meydûm. From them came the initial spark for the entire pyramid age which triggered later developments.

The Importance of the Step Module

From the indicated complex situation it follows that the reconstruction of the processes on the pyramid construction sites is to be sought in a linking of all listed aspects. Saqqâra makes it clear: the geometric pyramid was not the goal, it was the result of the construction process - basically just the side effect of a relatively subordinate auxiliary construction (the edge measurement and control).

The decisive development step was Djoser's step pyramid, namely as a method to organize and technically accomplish a large construction site at a previously unimaginable height, because higher buildings than two-floor houses, reed halls and mastabas had not been erected before. In Saqqâra, the step pyramid was initially developed from the superimposition of mastabas, i.e. the scheme of the mastaba was transferred to a greater height.

In a step pyramid, each higher step is set back from the lower one on all sides. The construction principle here was that the edge walls of all steps were built up to the base line, i.e. the building consisted of many shells or layers in a horizontal section at any height, comparable to onions. However, these stepped rings were built in one go and only slightly offset in height from one another. The fact that they were built offset from each other is evident from the sloping layers of the masonry and the sloped retaining walls. The layers of stone were laid at right angles to the retaining walls, i.e. inclined inwards; at that time it was not yet possible to carve the mantle stones in the trapezoidal shape required by the inclination.

[1]Müller-Römer [1], p. 63, 64
[2]Lehner [2], p. 102
[3]Maragioglio/Rinaldi [3], VI, fig. 4; Lehner 2017, S. 418
[4]Edwards [4], p. 185
[5]Lehner 1997, p. 16/17

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Each layer could therefore only be laid when the inner layer was already several stone layers high; the next outer layer leaned against the already finished masonry. The layers formed narrow construction sites in strips, arranged in a ring around the inner core. The principle of the steps thus had a direct impact on the construction processes. The additional effort that resulted from this shell construction must obviously have had a justification in the approach.

It is natural to relate this fact to the construction of ramps, but also to the mastery of size and geometry. The step pyramid was both scaffolding and measuring module system at the same time, for its vertical and horizontal dimensions are based on the nature of the geometric shape; each step had the same height and width. This wasn't about accuracy; the module system of the step pyramid was important precisely because the surveying was initially rather rudimentary. In addition, the construction site did not form a uniform level. As a result, a certain proportion of the increase in height took place within the structure itself, which above all had the advantage that it was possible to work with a flatter gradient and better maneuvering options. Even if the construction progress increasingly forced the transfer of transport to the outer ramps, the partial relief was significant; on almost level ground, one or two men were enough to move a ton of stone[6], while every increase in gradient meant an increase of manpower.

We also have to keep in mind that there were probably no plans for the pyramid construction sites, even most studies suggest something else. Certainly, the construction of the burial passages and chambers followed at least sketchy plans; and they are attested for the late period[7]. For the construction of the pyramid, only few specifications were required: the dimensions at the base, the step measurement (or the inclination in the case of the „true" pyramid) and the cardinal direction. The pyramidal or royal cubit was the unit of measurement. The steps of the step pyramid themselves formed this measuring and axis framework, based on their basic geometric idea. Even much later floor plan drawings are limited to very basic definitions. This also corresponds to the practice in traditional, vernacular building such as earth building in the Yemeni Hadramaut[8]. Here, as in Egypt, the introduction of adobe bricks marked the first step towards modular construction.

Such determinations could not be practicable without a three-dimensional grid or module. However, the rough, very irregular masonry of the first pyramids was not suitable for module markings. In addition to their static function, the shell-like stepped walls would serve as such a modular framework. Different degrees of precision in construction reflect different levels of skill, to put it in modern terms. The enormous edging and leveling precision (at the Khufu Pyramid) was achieved by specialized senior construction managers and the high priests; the fitting and alignment of the mantle stones were the task of the executing stonemasons, i.e. a small team on site. Yet there was another, middle level, which has been overlooked so far, but had a crucial function in building practice. There must have been a method by which the daily work schedule and general coordination and accounting had to be carried out. That's the foreman's job: today, as then, he is the intermediary between the planning level and implementation by the work crews.

Let us imagine how the team of Ahmose in the Green sa[9], as one of the five work gangs on the pyramid construction sites was called, was assigned their place of work in the morning. With a construction area of 200 by 200 m at the base of the Khufu Pyramid, the team had to be assigned an exact job. An indication like "left behind, next to the team of Hori and behind that of Sinuhê", would hardly have worked. And their work performance had to be recorded – it is hardly imaginable to carry out such a large construction site without some form of work or performance control; it would also contradict everything we know of Egyptian civilization[10]. The daily workload could only be measured if there was a module grid that was fixed on the construction site. Transport corridors also had to be kept clear and relocated regularly so that these areas could also continue to be built. For all of these processes, some form of workable module was mandatory.

In fact, there is evidence of markings with paint or carvings, and a module is recognizable at every stage of the building program. It begins with the mastabas, like No. 3357 in Saqqâra[11]. The ground plan of the mastaba with its "palace chambers" is clearly defined by a grid. The building is obviously divided into three sectors of equal size lengthways and widthways, and lengthwise each third is divided in half (Figure 2). The importance of the module is reflected in the hieroglyphic sign for 100 in the form of a rolled measuring rope[12].

[6]Chevrier, after Arnold 1991, p. 280
[7]Badawy [5]
[8]Marchand, Leiermann [6], p. 119, 141
[9]Lehner 1997, p. 224
[10]Edwards 1947, p. 180
[11]de Cenival [7], p. 48
[12]Arnold [8], p. 252

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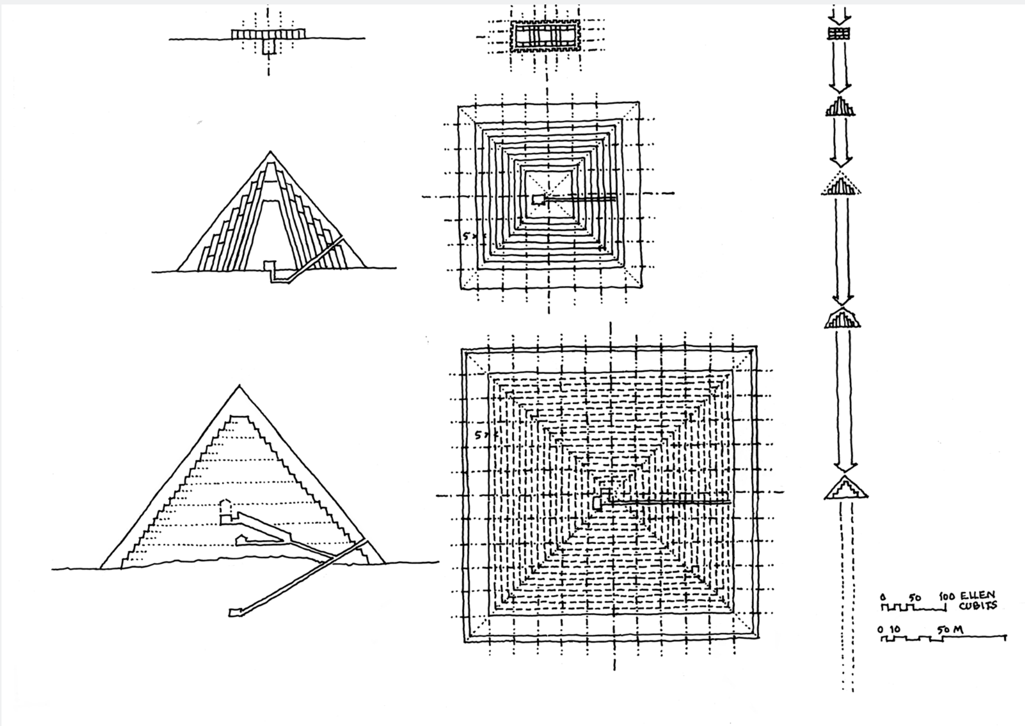

Figure 2: Pyramid phases and module of measurement: a) Mastaba 3357, Saqqâra; b)Meydûm, E 1-3; c)Khufu Pyramid.

In general, the arrangement of uniform elements in their geometric order remains a fundamental feature of ancient Egyptian art. Even in the Old Kingdom such principles of order applied to the palace facades and the sarcophagus paintings designed according to them. Architectural floor plans and settlement patterns are also shaped by such sequences and additions, as was also the case for the agricultural field patterns of the Nile valley.

In the case of the step pyramid with inner buttress wall system, the inner plan grid was inevitably given and specified the building division here. In the case of the Djoser pyramid in Saqqâra, the decisive step is clearly visible in the transition from the mastaba volume to the pyramid, i.e. to the square base. And even in the late stage of the construction of the great pyramid, the construction pattern can be read indirectly. If it should be confirmed that the masonry core of the Giza pyramids was built in horizontally aligned stone layers without inner buttress walls, this construction method requires a construction grid. A large area of up to 200 x 200 m could not have been aligned if either a network of dimension lines or dimension points had not been used.

The Ramps

Since different development steps can be observed in the construction of the great pyramids, this should also apply to the ramp construction. This was therefore more a system of construction methods that were gradually adapted, whereby the initial form was certainly a very simple one. In general, the transport on the ramps was carried out by human teams using rollers, which were wetted by water carriers in order to reduce frictional resistance. The stones from the local quarry or the delivery point on the bank were brought to the building site with oxen, and water from the next branch of the Nile, straw, food and beer as well as plaster were brought to the building site by donkeys.

Preserved remains of ramps contain only fragmentary indications for the reconstruction of their design[13]. There are four ramps on the small pyramid in Sinki, each facing the pyramid, which undoubtedly form the simplest basic form of the ramp. Their use is thus documented, but there are serious reasons against assuming that the ramp type perpendicular to the pyramid sides is also used for the large pyramids with heights of up to 150 m. Such building heights would hardly been constructively and functionally manageable. Ramp levels would have had to be constantly modified at full length as the construction progressed – and how could they be used while been modified?

All other remains of ramps found, such as in Saqqâra (at the pyramid of Sekhemkhet) as well as in Lisht and Abu Ghurâb, are either too fragmentary to allow further conclusions or it is even questionable whether they were not "only" transport routes to the construction site[14]. The remaining grinding slopes lead to the foot of the pyramid[15], which suggests that ramps were laid parallel to the masonry and in any case not perpendicular to it.

[13]Müller-Römer [1], p. 41 ff.
[14]Lehner 1997, p. 202
[15]Arnold [9], p. 19 f.

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Traces of parallel walls have been found close to the south-west corner of the Khufu Pyramid, interpreted as retaining walls of a casemate-like ramp leading from the quarry to the building in a south-north direction[16]. A frequently cited reference is the Rhindh papyrus[17], in which a ramp is described as an arithmetic problem, which corresponds to this basic type of vertical ramp. The ramp assumed there is 300 m long and 30 m high, so the gradient would be 10%. This calculation example is no proof, but shows that the assumption of such a building was a reasonably realistic idea for contemporaries.

The retaining wall of the ritual accessway to the Pyramid of Cheops also towered up to 30 m at the edge of the rock[18]. As a ritual structure, this tunnel-like processional way could hardly be compared to a building ramp; after all, retaining walls of a similar height were possible in principle. One could set this 30 m as the maximum construction height of a vertical ramp; but for a provisional ramp structure, this height is not particularly plausible. And the grinding slopes leading to the base of the pyramid speak decisively against such high and correspondingly long ramps[19]. It also had to be possible to temporarily store and maneuver between the runways and ramps so that the approach to the ramp can be located close to the pyramid mantle.

This scenario leads to the assumption of lateral ramps in cases where the vertical ramp was no longer practicable. The ramps on the sides corresponded closely to the construction of the step pyramids. Like Hölscher, but also Croon, Landt and Müller-Römer[20] in variants, I therefore assume that laterally "docked" work ramps were built in the module of the steps of the step pyramid, i.e. the ramps constructed on each "terrace" level led up to the level of the next (Figure 3).

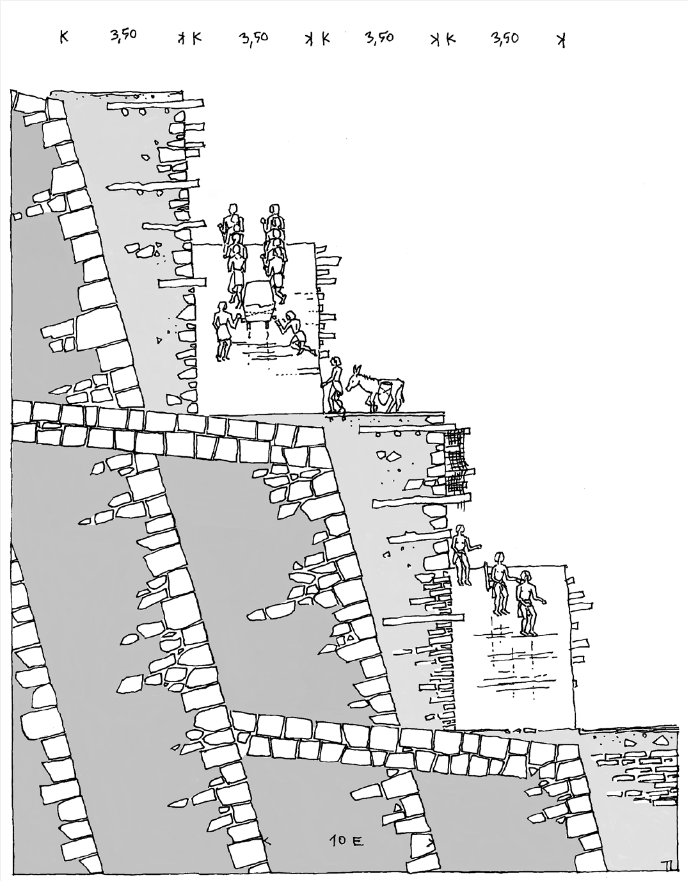

Figure 3: Ramp construction of a step pyramid; Cut at medium height.

Above all, however, the critical bottleneck is the calculated minimum transport cycle for the Khufu Pyramid of about one stone with an average weight of one and a half tons every 3 to 5 minutes that had to be moved (some suspect an even faster working cycle at the Red Pyramid[21]). Some scholars consider this speed to be "totally unthinkable[22]", but these concerns are particularly true for hypotheses based on mechanical aids. With a winch, for example, each stone would have to be tied, pulled down the ramp, detached, and maneuvered before the next stone could be harnessed.

[16]Goyon 1977, p. 146
[17]Arnold 1991, p. 98
[18]Lehner 2017, p. 185; Goyon 1977, p. 112 f.
[19]Arnold 1980, p. 18
[20]Müller-Römer 2007, S. 177
[21]zB. bei Krauss, Müller-Römer, 2007, p. 115
[22]Müller-Römer 2007, p. 153

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It is the dilemma of the technology-oriented theories that they cannot offer any significant contribution to increasing the transport cycle on the ramps, which was the main challenge. Lehner's NOVA experiment proved that a pulling power of one third of a ton per man is realistic for flat ramps[23]. This specification refers to slip tracks of 6% and would have to be reduced accordingly for ramps of 10%. However, the example shows that the length of the carriages could be limited to about two dozen men, which in principle makes the transport cycle of about 3 minutes per ramp seem possible. Edwards[24] and Goyon[25] come up with similar numbers. The real challenge lay in the geometry of the structure and the coordination of the processes.

The height of the steps of the step pyramids was about 9 meters, the width about 7.5 m, and the slope of the step walls corresponded to a width of about 2.5 m. The net depth of the steps was 5 m (10 cubits), which is also the same width of preserved ramp fragments. The transport of stones with an edge length of approx. 1 m required a width of 5 m when led by pairs of oxen and 3.5 to 2.5 m wide for human draft teams[26]. Chevrier assumes only one draftsman per ton of stone weight[27]. Next to it there had to be space for supervisors and helpers - brakemen, greasers, water carriers, who belonged to every train crew.

All of this speaks in favor of a standard width of 5 m or ten cubits for the laterally adjacent ramps. In ancient Egypt, round decimal dimensions were preferred, which is evident in almost all pyramids. The question now is whether there was one serpentine ramped way up covering one pyramid side, or several.

"Multi-lane" ramps, on which two or more train crews could work in parallel, are often proposed and form the basis of most reconstruction drawings in order to equalize the calculated transport flow[28]. On such ramps, the return transport could have taken place with empty sleds on the valley side, where the ramp was less loaded[29].

However, there are some objections against such an assumption. The ramp fragments that have been preserved, even in the Khufu pyramid, are almost 5 m wide[30]. It consisted of two parallel walls about five feet thick with an equal gap between them. Lehner sees this construction as part of the substructure of a much wider ramp, but that's pure speculation; the distance between the walls rather speaks against it. Trouble-free working was very important; every accident would disrupt the flow of transport. Parallel train crews might work on a grinding track, but the risks to the flow of transport were too great when climbing up the construction sites. Separate parallel ramps would have been more practical; but that would have increased the construction effort exponentially, and the spatial organization on the building site also speaks against such a scenario.

The train crews went down the valley with the empty sleds via the - probable - second route, where water and timber for the scaffolding were transported. The numerous crews also climbed up and down here: the construction site workers and stonemasons as well as informers and supervisors, but also the numerous replacement teams for turning maneuvers, for example. They were able to get to the work site on the turning platforms via branch bridges specially built in the corners between the turning platforms of the two ramp systems, so that they could get to the correct height near the work site without disturbing the heavy goods traffic (Figure 4).

The assumed basic dimensions of the ramps of 5 m (10 cubits) result from the shell dimensions of the step pyramids. For the train crews with their roles, train sleds, water carriers, overseers, helpers, etc., this width was not lavish, but practicable. Watering was used to improve glide (as be seen on the Djehutihoteb relief).

Several ramp types are conceivable, as the findings show. Ramps were temporary constructions, but for several years they had to allow the transport of heavy stones. According to Mark Lehner, mobile sand is unsuitable, while rubble in mortar is much more solid and also readily available[31]. In Zawjat al-Arjân, traces indicate brick foundations[32]. Mud brick ramps, like those partially preserved from the New Kingdom on the pylon in Karnak[33], were therefore an option. Incidentally, the remains at Karnak also contained a switchback. In any case, as evidenced by remains, the ramp surface was secured by planks.

According to Goyon, moistened clay is so slippery that a load sledge pulled on it requires minimal effort[34]. However, it is precisely this circumstance that speaks against the type of mudbrick ramps he favored. Although the slipways were lined with palm trunks or planks, constant watering and load use would inevitably have resulted in a mud bath that was neither stable nor practical. The mud construction sites in the Hadramaut, in an even hotter climate than northern Egypt, are veritable mud landscapes because of the necessary mixing with water, in which the workers wade knee-deep in mud. Wet clay ramps would have required constant repairs which would have undermined their stability. In later pyramids, adobe bricks were used for the core and for the ramps, but the transport of bricks could be done by donkey and did not require heavy loads. Hewn stones were transported in Karnak, but in manageable quantities and heights.

[23]Lehner 2017, p. 413
[24]Edwards [4], p. 210 8 Leute à 2,5 t
[25]Goyon 1977, p. 94 f.
[26]Müller-Römer 2007, p. 177
[27]de Cernival 1964, p. 145
[28]Dunham [10], p. 159
[29]Goyon [11], p. 163
[30]Lehner [2], p. 202

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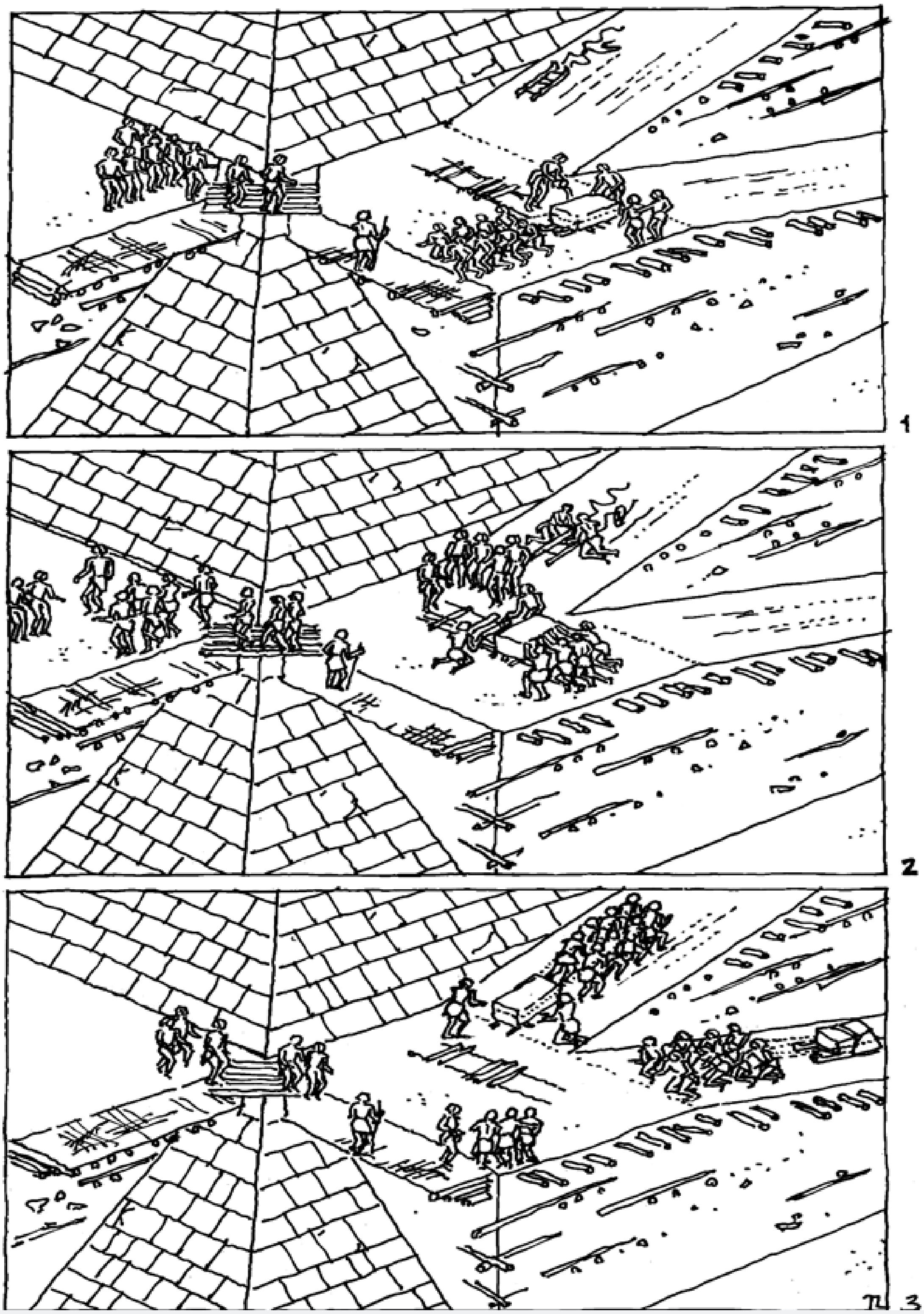

Figure 4: Phases of a turning maneuver.

[31]Lehner 1997, p. 222

[32]Stadelmann [12], p. 75

[33]de Cernival 1964, p. 60 Arnold 1991, p. 96

[34]Goyon 1977, p. 146 ff.

[35]Goyon 1977, p. 109

[36]Lehner 1997, NOVA-Experiments with 12 %

[37]Müller-Römer 2007, p. 180; Arnold 1991, p. 99

[38]Goyon 1977, p. 147 f.

[39]ibid., p. 149

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The inclination of the side embankments of the ramps is unknown, but flat slopes as in dyke construction would be extremely voluminous and not suitable for steep ramp serpentines, especially not in the module of the step pyramids. Instead of a flat embankment, the ramps probably had almost vertical retaining walls. The "Casemate Wall" at the Khufu Pyramid supports this assumption. A ramp gradient of up to 10% is generally considered to be well practicable for stone transport using rollers and sleds[35]. Experiments show[36] that it was still possible to work with 12%.

The lower steps allowed the use of teams of oxen with wooden sledges. Such are known, for example, from a relief in the tomb of Hetepherachti, although not documented for the ramp transport[37]. They were probably indispensable for heavy transport, especially of the capstones of the burial chambers. Animal transport can therefore be assumed up to their installation height.

Animal teams were a particular challenge on the construction sites. The animals should not fall or become wild - oncoming traffic was hardly conceivable. A circulation over two ramp routes was indispensable here. There could also have been dedicated ramps for animal transport, possibly with a steeper incline, but avoiding turning points. Railings on the crash side could have been fastened by a grid of palm trunks[38] with poles and bundles of reeds just below ramp level and covered with reed mats.

As the heights increased, side lengths of the pyramid steps decreased, making it more and more difficult to maintain the practical inclination angles for pull ramps. With a width of approx. 5 m, with 10% and 9.5 m step height, a single-flight ramp had to be at least 100 m gross long, since the turning points at the end also have to be taken into account. In the case of higher, i.e. shorter steps, this length was no longer given, here a double-barreled ramp had to be created for each step, which resulted in the maximum width of 3.5 m.

As Goyon suggested, ramps became narrower the higher they went[39]. Assuming a team of 20 men from three rope trains of 7 people each, 3.5 m should have been sufficient, and even a ramp width of 2.50 m with vertical retaining walls was sufficient for paired rope teams, which allowed three-course ramps per step. It wasn't a lot of maneuvering space, but that was at the top of the pyramid, where most of the structure was already completed and only a relatively small amount of space was left to manage.

On the top two steps of the step pyramid, where the ramp lengths became smaller and smaller, there was the possibility of changing to a spiral ramp. Their disadvantages in the lower area did not apply up here, and the hindrance to the surveying was no longer significant here shortly before the construction was completed.

The Ramp Footprint of Meydûm

Apart from the interesting observations in regard to the three building stages of the pyramidal torso of Meydûm, this site offers a remarkable detail which seems to be the only authentic trace of a ramp structure at a great height, namely on the fourth and fifth steps of the eight-step pyramid extension E2. It is not a ramp structure itself, but rather its negative imprint on the core structure. At least this is what it looks like; any other explanation is difficult to imagine and has not been presented to this day.

Figure 5: The pyramid of Meydûm from the north-west with the pyramid mantle exposed.

[40]Arnold 1991, fig. 3.32, p. 83
[41]Borchardt 1928, p. 20 ff.
[42]ibd., p. 22

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This recess, only faintly visible if not sharpened by morning light, is located approximately in the southern third of the east face of the step pyramid[40] (Figure 5). This recess is about five meters wide and offset a few centimeters inward from the rest of the outside line of the cladding. The two side edges are carefully worked; its course is slightly sloped. This detail looks like a construction joint to an extension that was later demolished. This extension would have been about five meters wide and would have been flanked by very steeply sloped side walls.

Petrie now made the observation, picked up by Wainwright and Borchardt, that this recess is exactly aligned with an older causeway that runs somewhat south of the ascent leading to the mortuary temple, which is clearly visible today (Figure 4). This track leads at a slanting angle but straight from the valley to the pyramid and cuts into the terrain with side walls[41]. It appears logical to reconstruct a ramp in this route, about 5 m wide and up to a height of about 60 m, with almost vertical walls on both sides. The result would be a strange and daring building, the plausibility of which is generally rejected and can be ruled out. And indeed, the finding itself contradicts Borchardt's reconstruction. The ramp impression on the fourth step has a width of 4.95 m, that on the fifth step measures 5.36 m. Borchardt gives these measurements according to Petrie[42]. Such a width is consistent with other known ramps and also with the step width of roughly ten cubits. However, had it been a full-height vertical ramp to the base of the seventh tier, with steeply sloping side walls, the ramp should have been less wide at the top than at the bottom. Consequently, this possibility is ruled out.

Nonetheless, there must be a relationship between the track and these ramp joints. Although a continuous ramp of six steps is out of the question, there was a connection between the ascent and the arrival level at high altitude; there must have been a construction on this axis, by means of which the stones were brought to the great height. While the grinding tracks in Dahshûr and Giza ran towards the corners of the building site, the route in Meydûm was aligned towards the center of the pyramid. This difference is certainly due to the respective ramp system; E2 was built before the pyramids at Dahshur and Giza, so this speaks for a working method that was still used at E2 but was replaced by other working methods at later pyramids.

When the slipways or ascents in Meydûm lead to the center of the building, they were obviously laid out towards a central post, which, as mentioned, was necessary anyway for the pyramid layout in its initial phase. But there was one more important aspect. As mentioned, in the case of the shell construction method, the retaining walls inserted into one another and their respective infill masonry laid in sloping layers were built in several square rings of 5 meters each, built at the same time, albeit slightly offset in height due to the sloping construction method. This only worked if the delivery took place in the middle of the construction site, i.e. across the retaining walls towards the middle field, which was built first, namely at a greater height than the following rings.

The stones had to be delivered from the outer ramp directly to the middle field, the other shells could be supplied from the same route. If the outer ramp had been attached to one of the corners of the building, the transport route on the construction site would have come up against several retaining wall corners and would have had to meander through the construction site strips of the different shells. Since the transport route had to be constantly moved back and forth a few meters as the construction progressed, only a route to the middle field was practicable.

The zigzag ramps on the east side each led to the north, once per step back and forth, 2.5 to 3.5 m wide, depending on the incline of their lateral walls. It is possible that at this stage they were wooden constructions filled in with rubble; in the case of the later pyramids with larger stone formats, solid construction forms were used. This scenario would emphasize the need for massive towers to counterbalance such wooden ramp constructions.

Another reason for retaining the basic route relates to the construction of the ramps themselves. These were ideally reached on the landings of the steps, i.e. on the horizontal, 5 m wide strip of the step pyramid. The steps were about 30 feet high, walls of this height had been standard since Djoser times; also for retaining walls of ramps. The most exposed or constructively most demanding point in this constellation was the turning point at the step height, where the upper ramp ended, because there the maximum construction height per step was reached, namely the full step height. In addition, the turning maneuver took place here. And then this point was free on at least two sides, thus forming a tower-like bastion (Figure 6). For this, the hitherto conventional shell construction offered a method, according to which the building mass was erected in sectors that were built along steeply inclined walls or leaned against such sloping walls. The ramp at the side leaned against the "tower" in the same way, the shape of which can still be seen today through the construction joints.

[43]Borchardt 1928, p. 23/24
[44]Arnold 1991, p. 86
[45]Müller-Römer 2007, p. 60, 62, 65

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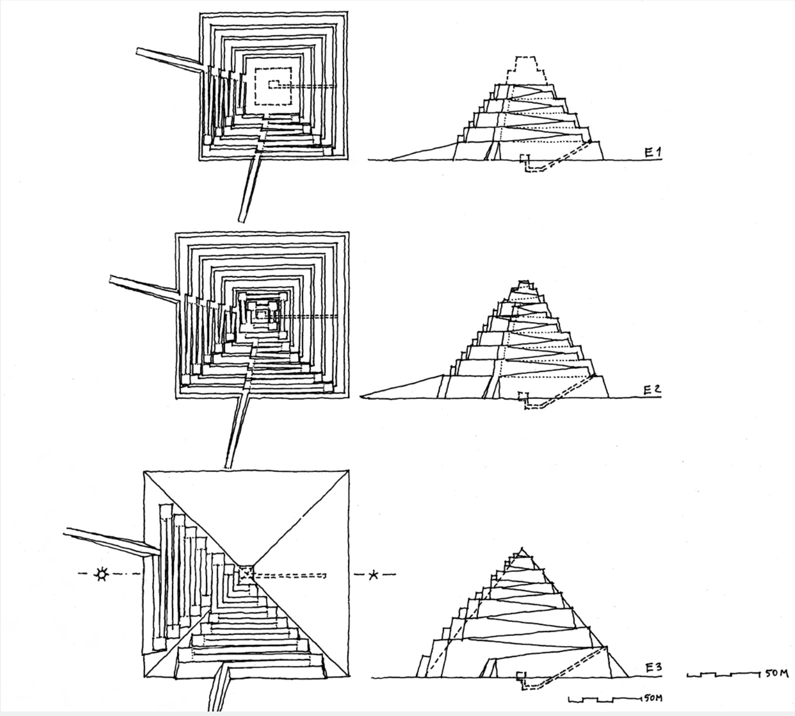

Figure 6: Meydûm building stages.

Figure 7: Rope tensioners in agriculture; Tomb of Nakht, West Thebes.

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Figure 8: Pyramid of Khafrê.

Here it should be emphasized again that a measurement from the center without an edge check was impossible. It was possible to define the central axis by a plumb shaft, but the findings rule out that such a shaft ran the whole height of the building. Anyway, such a shaft would not have prevented any twisting of the edges. The center marking alone was therefore not sufficient, edges and centers had to be controlled periodically. A marking of the central axis is evidenced by red line markings in the Menkaurê Pyramid, where they became visible through Caliph Ma'mûn's demolition attempts[46]. It is an essential useful property of the pyramid that its center can always be found by crossing the diagonals from the edges and vice versa. However, since a continuous fixation of the central axis was impossible, periodic edge measurements were essential.

Over the long edge dimensions of the pyramids, it was certainly no longer possible to keep the rope bracing absolutely straight. For this reason, bearings had to be taken, which were already necessary for the north adjustment, using a gnomon[47]. However, this was also done, at least originally, with the help of cable bracing. This is illustrated by inscriptions, according to which the king, together with the goddess Seschat, hammered in posts that were connected by entwined ropes[48]. As mentioned, leveling was also carried out on a detailed scale using stretched ropes and distance sticks. Bearings by supervisors were a periodic process, the results of which were recorded by notches or scribing marks; However, stretched ropes were part of the daily work routine.

In addition, juxtaposed rulers were used as well, of which found examples are cubits long[49]. Under the name qassaba they were traditionally common among farmers in the Nile valley. But rope guying was more practical for longer lengths; In pre-modern construction, such as in Yemeni earth building, straight-line construction without daily tightening of lining ropes is simply unthinkable.

The slightly concave sides of the Bent and Khufu Pyramids point to the sagging of the ropes along the sides at a greater height, which could hardly be avoided with an edge length of up to 200 m[50]. They could easily have been corrected by bearing, but this was done only from time to time, while the rope suspension was indispensable in the daily construction process and thus probably caused in the sagging. Once the baseline had been marked, the desired slope of the side surfaces (in Giza one cubit to five and a half handbreadths or 52 degrees) could be adjusted using templates. A rope fixing to the baseline every 10 cubits (5 m) would correspond to the step module and the ancient Egyptian decimal system. This corresponds to measuring holes at a distance of 10 cubits in the mantle of the Khafrê pyramid[51].

[46]Lehner 1997, p. 122
[47]Hawass/Lehner [13], p. 406; Mendel, p. 93
[48]Bindel [14], p. 107
[49]Hawass/Lehner [13], p. 432
[50]Lehner 1997, p. 212/213
[51]Haase [15], p. 24, 26

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For the exact cutting of the cladding stones afterwards, wooden jigs were certainly used, which specified the *sequed* dimension of the inclination, but bracing the pyramid inclination was necessary for the measurement of the mantle. Since the stones were individually adapted to the neighboring stone during the finishing of the cladding, the outer building lines had to be checked again and again.

One of the difficult features of the pyramid was that its external dimensions varied at each height. The Egyptians could only calculate simple fractions and were therefore only able to calculate and measure the proportion of the *sequed* according to height and width at regular intervals. Since the pyramid tip could not be used as dimensional reference, the pyramid base had to be roughly traced for each layer of stones using the central axis and the corners through the diagonal; the notches are part of this process. As the reference to the diagonal had to be recognizable during the whole construction process, the height dimensions already marked on the building could be adjusted again at any time (Figure 9).

Figure 9: Pyramid mantle of the Pyramid of Menkaurê.

The decision to use a "true" pyramid instead of a stepped structure corresponded to the state of the art at this point in the pyramid program, but required a number of necessary developments and solutions to new challenges. The most important innovation was, of course, the construction of the sloping pyramid mantle. The construction ramps "sat" on this mantle, on which protruding stones offered a certain support. Such stones are partially preserved[52], but they were by no means sufficient for the stability of ramps for heavy transport. Despite the still unworked outer surfaces of the mantle stones, the huge sloping surface did not offer a good working surface for later finishing work, for example. It can therefore be assumed that temporary scaffolding was erected on the exposed lateral surfaces, which grew in height with the construction. The use of wooden scaffolding on the pyramid construction site has not been discussed so far. In any case, Egyptian depictions of wooden pole scaffolding show light constructions fixed by node connections (Figure 10).

Today there is general agreement that the smoothing of the outer cladding was done after the stones were set. This smoothing then logically took place from top to bottom, which also fits in with the fact that, for example, on the Menkaurê pyramid, the lowest layers were not smoothed. This means that the smoothing only started after the onset of the pyramid capstone.

By the way, scaffolding of poles is also a good explanation for the strange bosses of many of the granite cladding stones on the Menkaurê Pyramid. These have roughly the form of short logs and are set in continuous rows at the base and top of the granite cladding (Figure 9). However, as a support for horizontal rod constructions, which were connected and knotted with vertical timbers, this form was obvious and appropriate.

Figure 10: Timber scaffolding, SPK Berlin.

[52]Stadelmann [16], p. 51
[53]Hawass/Lehner 2017, p. 194
[54]Lehner 1997, p. 196
[55]Lehner 1997, p. 222
[56]Goyon 1977, p. 67

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The light wooden scaffolding was unsuitable for transporting stones. This had to take place on massive ramps, which at greater heights could no longer have a width of 5 m due to the geometry of the pyramid. For this reason, the mantle stones at the top received their shape, which is difficult to determine due to the oblique shape of the top, before they were brought to place and were not hewn in situ as before[53].

As a matter of fact, the geometry of the "true" pyramid made the completion of the top a challenge, as maneuvering space became scarce – and indeed, it took Sneferu´s lifetime to overcome this challenge. It became difficult to provide ramps with the needed length and width and with an acceptable gradient. Inaccuracies in the area of the top of the Khafrê could indicate that larger deviations at the top were actually accepted or could not be avoided[54].

A theoretical option to compensate the tight space for ramps on the summit of a sloping "true" pyramid could have been even larger ramp structures in the lower level. Yet this would have required large additional volumes of ramp substructures and could have made the whole structurally critical. In any case, it got tight on the last few meters of the pyramid for the ramp construction. And the Pyramidion, the pyramid-shaped capstone weighing a good 5 tons, still had to be brought to the summit. This stone was decorated with inscriptions and golden sheets; it had a high symbolic, spiritual and aesthetic significance and its putting in place gave an occasion for an extensive celebration for the workers, as can be read from the depiction in Abu Sîr[55].

More than any other pyramid the partly collapsed Meydûm Pyramid shows how flexible the ramp system described here could be used for different types of building. This pyramid has been built in three stages: a step pyramid E1, a stepped expansion E2 and a geometric pyramid E3. If the expansion construction sites - with their need for a complete ramp structure for each construction phase – had proven to be ineffective, it should be not clear why this constellation was used again and again (in Saqqâra, in Meydûm at E2 and E3). On the contrary, the approach must have proved to be quite suitable. At all three building extensions, the width of the extension was approximately 10 cubits, so one can speak of a tried and tested procedure here.

In any case, this constellation supports the hypothesis of lateral ramps as the basic form; it could be varied in the lowest and highest zones. Any other ramp shape would have been disproportionate to the extension in terms of volume and effort.

The extension of E2, for example, required work on an elongated construction site 5 m wide, which also included the transport route for the areas above. It is noticeable here that, as described, construction of P1 and P2 in Saqqâra and E1 in Meydûm was already organized in narrow strips due to the shell construction with inner retaining walls in a regular module. And these working strips were also isolated from each other, as they were each heigh-staggered, due to the inclined stone layers.

Beside, the analysis of the pyramid ramp system could even contribute to the interpretation of the Bent Pyramid with its "strange" inclination, that is widely regarded as the first ever sloped pyramid that has been built, as E3 of Meydûm was only constructed later. Based on experience with the step pyramids, it was clear that the construction of the ramps towards the top would be a challenge. In the case of the step pyramids, this problem could somehow been solved, as by a spiral guide on the top two steps; but on the inclined pyramid this procedure was ruled out, it offered no support for such a construction on the slopes.

It is therefore possible that the kink marks the level of the construction site, where it became clear to the builders that the continuation of the inclined surfaces with the same incline would no longer work with the ramps. Given a ramp gradient of 10 percent, a ramp length of 50 m and the pyramid inclination of 45°, a ramp width of 5 m was still possible up to this level. The ratio of length and width was no longer sufficient further up. Perhaps those responsible for construction were still in good spirits at the start of construction, to be able to solve this problem somehow - an attitude that is not entirely unknown in the technological history of mankind, if we think, for example, of the cathedral dome in Florence or the storage of nuclear fuel elements.

The question as to whether the decision on the buckling shape was formally intended or made out of necessity cannot be answered with certainty, but there is little to support the assumption that the decision to buck was primarily aimed at a weight reduction. The geometry of a sloping pyramid caused the challenge that with increasing height, it became more and more difficult to establish transport ramps with the same gradient upwards. There was no precedent to this case, it had to be dealt with in practical tests. If this hypothesis is correct, the kink marked the moment from which it was realized that a ramp supply of the top of geometric pyramids was technically possible only with a maximum gradient of the slope. Which slope could be feasible, Sneferu´s building masters could not calculate but the increasing difficulties made clear the actual gradient of the pyramid base was too ambitious (Figure 11).

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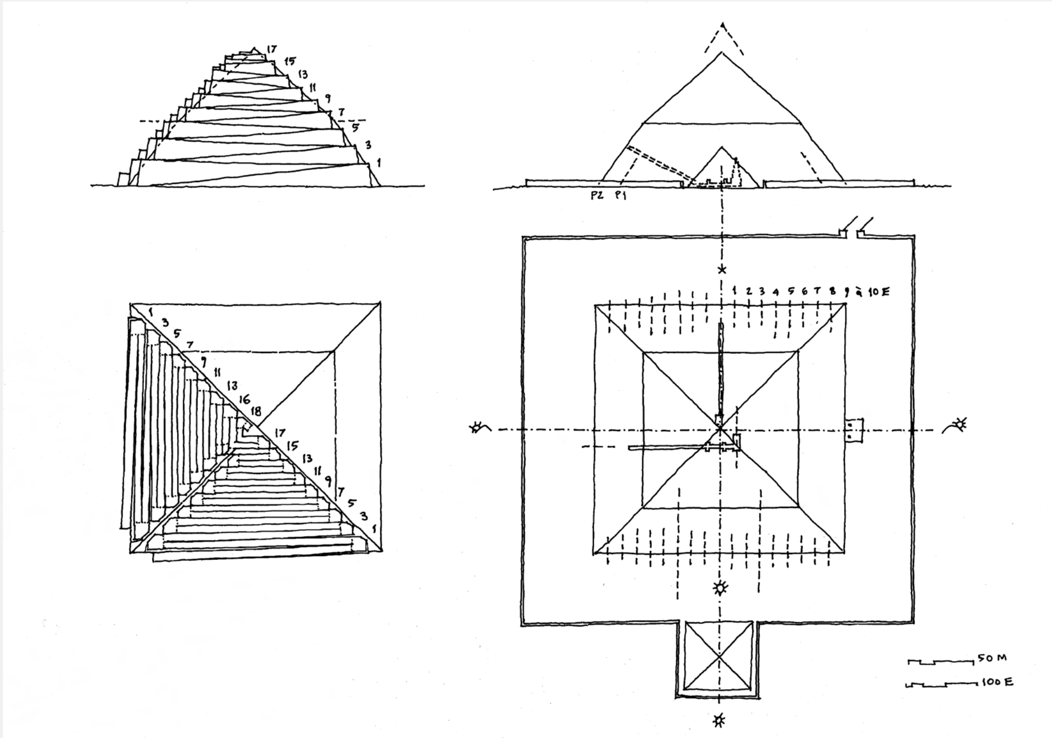

Figure 11: Bent pyramid, elevation and ground plan with building ramps.

The experiments at the Bent Pyramid were further developed with the Red Pyramid at Dahshur and with E3 at Meydûm, but eventually culminated at the Khufu Pyramid at Giza, where ramp building and construction efficiency reached their climax.

The Great Pyramid of Khufu

Khufu, actually Khufu-Khnum, with the Horus name Horus Medjedu, took over a prosperous, stable empire from Sneferu. The skills of the master builders had reached the limits of what was possible, even in their own self-image. In this mood, Khufu' sky-storming ambition is understandable:

My reign will be the greatest, the most glorious. She will surpass in fame that of the Great Sneferu, my father, the Blessed One[56]. Under Khufu the order and structuring of society and thus also the work processes were further developed, and the technical and economic possibilities could be applied even more effectively and in a concentrated manner than ever before or afterwards. Through a special harmony of all forces and processes involved, the king, whose only surviving portrait is a small figurine, became the most important builder of all times.

In the dimensions on the base line, Khufu adopted the dimensions of the north pyramid of Dahshûr and, with a slight deviation, the inclination of almost 52° at Meydûm E3, thus continuing with proven specifications. In Giza, a uniform building with this inclination was now completed with a significantly enlarged base area. Although the individual aspects of construction had all been tried and mastered in the Sneferu Pyramids, it represented a great challenge; mainly because of the strict geometry of a steep pyramid that allowed no deviation.

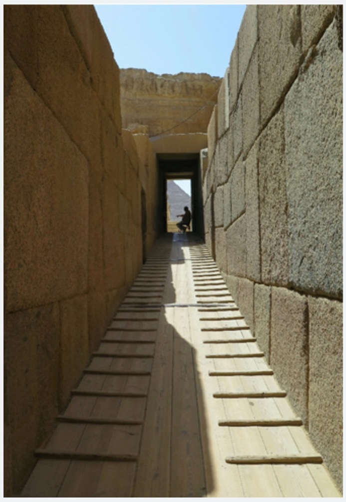

Figure 12: Corridor in the mortuary temple of Khafrê.

The result was the largest pyramid ever built. At the same time, it is the most sophisticated structure of the Pyramid Age in terms of construction, interiors and dimensions; a coincidence that underlines that this climax marked the limits of what was possible at the time. Only Khufu´s son Khafrê was able to at least come close to the model of the Khufu building, using the established capacities (Figure 12).

[57]Stadelmann 1991, p. 110

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Figure 13: Pyramid of Khufu, back stone rows.

The Great Pyramid was thus principally executed horizontally in layers of stone at the same height. The stones of the cladding from the quarries in Tûra and Ma'âdi are adapted to the height of the stone layers, but only the lowest layer of them has been preserved. A second row of stones was arranged behind the cladding, the so-called backing stones, which represented a bracket in the core masonry and were well interlocked with it (Figure 13). The stones of the cladding were also usually binders, i.e. arranged with the narrow side facing outwards, which also underlines the special care taken to ensure the cohesion of the masonry[57].

The height of the stone layers generally decreases towards the top. This makes sense in terms of stability and weight, and it corresponds to a practice that was not uncommon in pre-modern construction. The stones at the base were three cubits high, but the 201st layer (the last surviving of the pyramid, which may originally have had 210 layers) is two cubits high. The average stone height is a little more than a cubit, about 69 cm; a stone format that was still easy to handle in transport.

As the masonry reveals, insofar as it is exposed, the inner masonry follows the stone layers in principle, but less accurately than the surviving facing stones and the outer stones of the core. In this way, gaps within the layer could be filled with smaller stones or irregular formats depending on availability. Building rubble or desert clay was also used to fill in the gaps; such measures stretched the pace of work and material; work gangs that had fallen behind could catch up by this way.

Therefore, there was improvisation, but great care was taken to ensure that the casing was precisely fitted and joints were sealed to ward off sand and rain. The stones were roughly cut in the quarry and brought to the construction site and only finished in situ[58]. They were fitted between the stones already installed, the final processing of each stone was carried out individually.

The differing height of the layers can be associated with the strongly horizontally layered stone formation in Giza[59], which resulted in the availability of large, uniform stone formats. After the availability of a sufficient quantity of stones, the height of the stone layer was roughly determined and the stones were ordered accordingly and brought to the construction site level, where the gangs had to deliver according to these specifications, even the finishing was done according to individual cutting.

The astonishing precision of the leveling of the subsoil as well as the north orientation of this pyramid (apart from the spiritual meaning) defines a level of dimensioning, the precision of which in no way referred to the individual work processes, but it was their prerequisite. The leveling of the subsoil, on the other hand, was important as a specification for the uniform stone layers. Due to the rocky crest, the building ground was initially very uneven and the leveling was very complex; but that doesn´t mean leveling was not important. On the contrary, it shows how indispensable levelling was despite its costs – during the whole process.

In order to explain the precision of the subsoil leveling of the Cheops pyramid, Arnold assumed that the subsoil was flooded[60]; others reject this, as they have a giant artificial lake in mind. Yet as the Egyptians were masters of irrigated agriculture, a narrow leveling channel along the outer edges would have been sufficient, section by section created by repeated watering and hardened by the sun. The natural changes in the terrain that Lehner refers to were not an obstacle: the course of the ring canal was adapted to the topography by rock cutting or backfilling - this leveling was necessary in the completion of the pyramid base anyway. The rough level for canal construction was achieved by aligning short canal sections. Especially in desert areas people were very skilled in dealing with water channels, it was the basic technology of the oases and of the Egyptian civilization.

Assuming 4 liters per meter of the water consumed, it would have had to be procured by a hundred donkeys, each with two 20-liter hoses – hardly an unrealistic effort given the importance of the basic levelling. However, cistern tanks, which were fed by donkeys, were needed for the workers, for the production of mortar, for watering the rollers or sleds. In the desert region of Hadramaut in Yemen - at over 45° in summer - no clay building site is conceivable without plenty of water; and there in the past, in contrast to the Nile valley, only well water was available[61].

[58] Hawass/Lehner 2017, p. 442
[59] Stadelmann 1991, p. 109
[60] Arnold 1980, p. 19
[61] Leiermann [17], p. 241
[62] Lehner 1997, p. 202; Lehner 2017, p. 145

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The challenge now was to transfer the maximum efficiency of the technical possibilities to the procedure in the daily construction process, in which unskilled labor and savings played a role, as evidenced by occasional filling with rubble stones, mortar and desert clay[62]. This coordination had to take place under the constant performance pressure as expressed in the tight transport tact on the ramp. The calculated tact only applied to the transport ramp itself; arrived at the construction level, the transport routes divided. The processing of the stones took at least several hours. If we take as a basis the transport cycle calculated from the construction time and the building mass of one stone every 3 minutes, i.e. 20 stones per hour, each team would have two hours for processing and use. That wasn't enough for the mantle lining stones, which made up only a small percentage; as an average value, this is quite realistic. A good distribution of the work areas and the stones assigned to them was important. Only if this was perfectly organized could the extremely tight transport tact be maintained during the twenty years (or more) of construction (Figure 14).

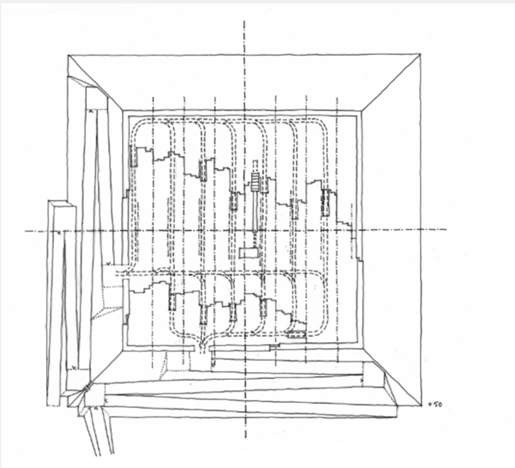

Figure 14: Pyramid of Khufu, hypothetical state of construction with a 20 cubit grid at +50 m.

Laying the mantle stones and their back stones was the task of dedicated construction crews, whose building site was one stone layer higher than the higher layer of the core, so that at least three stone layers were worked on at the same time. The delivery of the two stone types was coordinated. The location of the work areas and the delivery slopes with short ramps, if there were differences in level, also had to be carefully coordinated.

It was therefore essential to divide the respective building level into coordinates and to divide the work according to this module grid. It would not have been possible otherwise to have the various work teams work side by side in a coordinated manner, i.e. dividing up the work every morning, monitoring it, ordering and procuring the material required and, last but not least, accounting. All building measures of the Khufu period, including the western and eastern cemeteries and the workers' quarters, reveal the grid structure of such a modular arrangement.

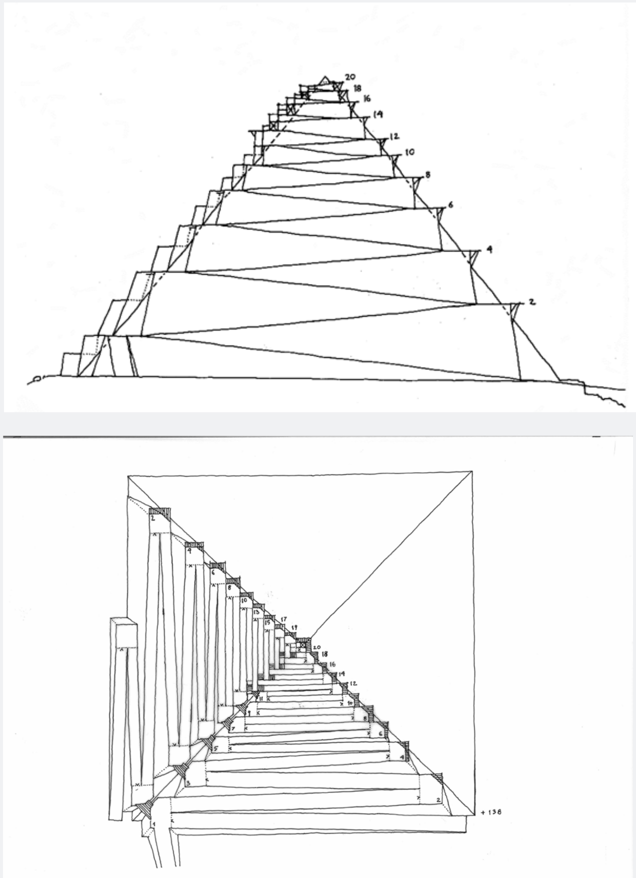

Figure 15: Pyramid of Khufu, ramp system upon completion of the top.

The module of the pyramid is not known, although traces of the relevant markings in the building may certainly be preserved and could theoretically be identified one day by chance. However, given the overall context, it is plausible to assume a parcel division in the decimal system of ten cubits in a north-south direction, since the delivery took place in this direction and the building lots were structured this way. A similar grid also divided the cemetery and the workers' town (Figure 17).

The structuring of the mass by a parcel measure of 20 cubits is very realistic. This corresponds to about ten meters and is a suitable dimension for a work zone in which a construction crew can work well. Five meters would already be too narrow; the work

63 Stadelmann 1991, p. 121
64 ibd., p. 154
65 Haase 2014, p. 44
66 Stadelmann 1991, p. 115
67 Hawass/Lehner 2017, fig. 8.6

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plot had to include the transport and setting of stones, but also the interim storage of stones and bulk material and sufficient maneuvering space for workers, helpers and relief supplies. The module of the last step pyramid was twenty cubits, too. And it is also the measure of perimeter courtyards at Cheops[63] and also at Shepseskaf[64], so overall it can be considered the usual base measure.

The transport routes along which the materials were to be delivered to the construction site also had to be determined along these dimension lines. These runways crossed the work area of the individual teams and therefore had to be specified by the senior site managers, within the grid. Of course, the supply ramp had to be constantly adjusted and relocated as construction progressed. Due to the particularly demanding work on the inclined cladding, it had to ensure delivery at all times.

As the outer dimensions of a pyramid constantly changed with the raising height, the work plots were dimensioned from the central axis. The center line was therefore of central importance, especially in the north-south direction. Their marking as a notch or red line has been preserved at various points in the pyramids, and the north-south marking in the King's Chamber also proves the importance of this line[65].

Depending on the different layers of stone, two or three construction crews may have worked at the same time on each "plot". On the north side, the construction had progressed further, here the next but one layer of stones had already begun, seen from the arrival side. Each "plot" led over two to three layers of stone, which steadily shifted to the south as the work progressed. Accordingly, if two or three construction crews worked per "plot", this would mean forty construction crews in the lower area of the Khufu Pyramid.

There is even an indication, perhaps even proof of this modular system, namely the so-called belt stones at a distance of 5 m, which Borchardt discovered in the Great Gallery of the Khufu Pyramid[66]. Originally it was believed that with these inner shell walls would be visible as in the early step pyramids. Today they are rather seen as traces of stabilization masonry. In any case, it is conceivable that this construction fitted into a modular division of ten cubits. It corresponds precisely to the advantages of a modular dimension that it can always be flexibly modified, i.e. halved, doubled or multiplied, depending on its practical use.

The simultaneous work of as many construction crews as possible was essential for maintaining work efficiency. Once a stone had been delivered to the place of use, it had to be processed and adjusted, balanced to its final position and precisely fitted using a lever; this work process is documented by semicircular indentations on the lower edge of mantle stones on the Pyramid of Khufu[67].

One cannot speak of planning in the modern sense. The inclination of the corridors, the mechanism of the fall barriers and the sequence of tombs and antechambers as well as relief chambers were three-dimensionally complex and had to be produced under difficult conditions underground: working models were indispensable here and they have also been preserved. On the one hand there is a wooden model of a burial chamber system from the XIII. Dynasty found in the Valley Temple of Amenemhet III at Dahshur[68]. Above all, however, there is a three-dimensional model built as a reduced building, which is known as the trial passages in the Khufu Pyramid[69] and represents the actually executed constellation in the great pyramid on a scale of 1:7. It is the oldest surviving mock-up in world history.

But plans were of no use in laying the stones; on the other hand, a mature modular system was essential. The periodically occurring layers, which appear like "annual rings" in the masonry of the Khufu Pyramid[70], for which different interpretations circulate, provide an indication of the work organization. They are layers of stone, one and a half to two cubits high, occurring at irregular intervals.

Their function is quite obvious: the leading construction managers were aware of the discrepancy between the precision of the basic dimensions of the pyramid and the inaccuracy with which the crews in the core masonry sometimes worked in order to meet the deadlines. In the case of the step pyramids, the steps were the yardstick by means of which the edges of the pyramid square and, at a regular height, the inclination could be rechecked and thus adhered to. This method did not work in an inclined pyramid. It was therefore necessary to readjust from time to time in order to restore the greatest possible precision, because this was the only way to achieve evenness and finally the edges to meet at the tip. The "annual rings" are evidence of this periodic process.

The name "annual rings" indicates why those layers are positioned in irregular distance to each other. One possible reason would be if the follow-up inspection was part of a rite at a certain time of the year. But then the distances would rather increase upwards. The relatively continuously layered rock deposits in Gizeh certainly determined the availability of the stone sizes and the height of the layers, but this did not result in any standardized, horizontally leveled surfaces in the practical construction process, especially since work was being carried out on several layers at the same time. In view of the enormous amounts of stones in areas of initially around 200 by 200 m, it was difficult enough to maintain a consistent stone height to some extent. Therefore, the compensating layers were necessary without requiring them to be regularly spaced. It is precisely the periodic sequence of these layers that underscores their organizational character.

[68]Stadelmann 1991, p. 109
[69]Haase 2014, p. 21
[70]Hawass/Lehner 2017, p. 430 Lehner 2017, p. 359 ff.

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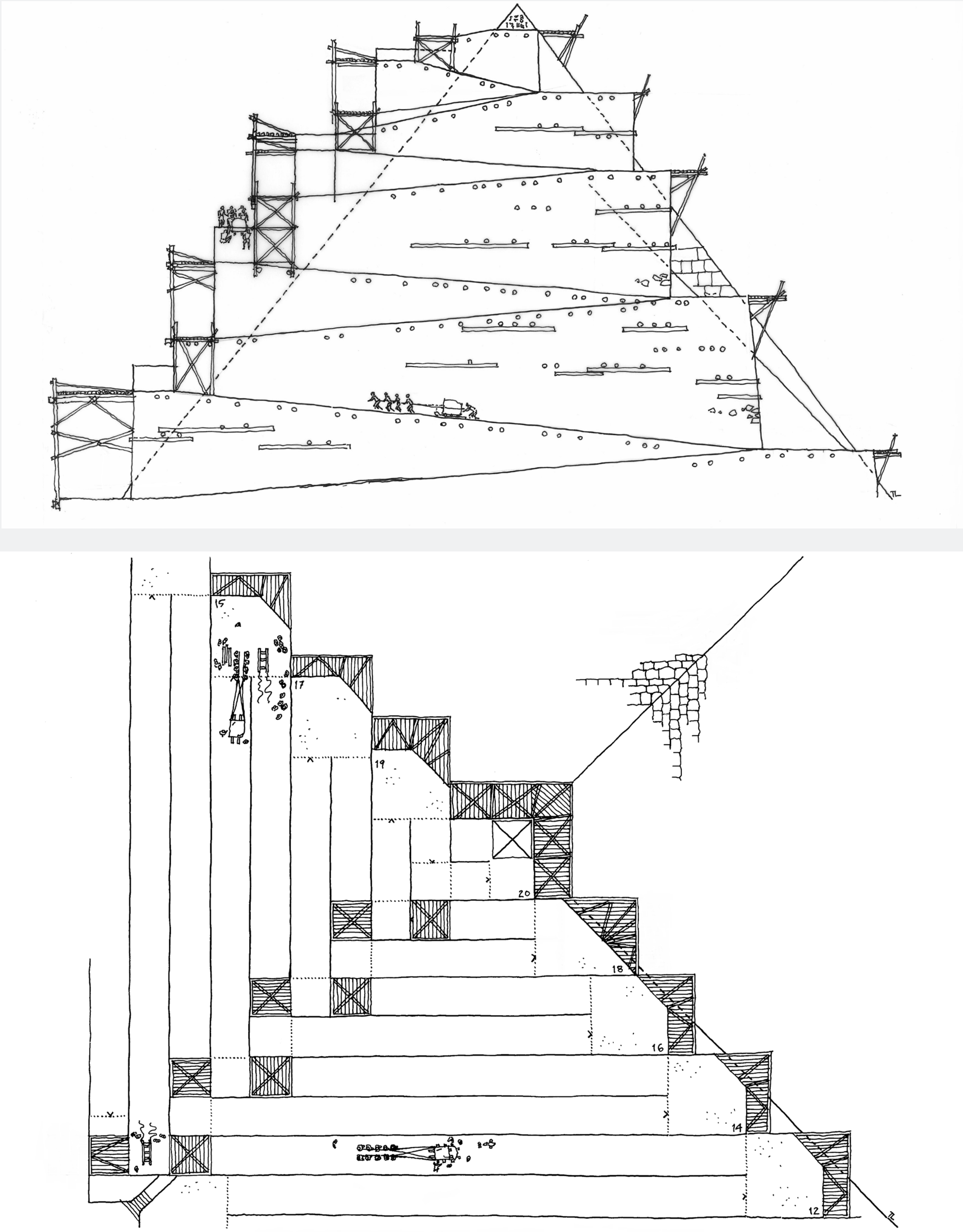

Figure 16: Pyramid of Khufu; Construction ramps at the top.

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The square pyramid could be fixed due to the edge alignment and control of the diagonals and the center as well as side lengths despite the irregular distances. The inclination could also be checked, because the height measurement was possible despite the different leveling layers. The height only had to add in cubits and hand widths and the appropriate *sequed* size determined, a simple arithmetic task. Once the precise measurement had been taken by checking the exact diagonals, the crews were able to go back to day-to-day work in the months that followed after this check.

The ramp system was certainly consisting of serpentine ramps on two working sides. In the case of the Khufu Pyramid, as in the case of the Red Pyramid, the slideways converge on the south-western corner of the pyramid. As tedious as a turnaround was to manage, in the same time it was a good opportunity to change the pulling crew. And the serpentine system was also flexible enough to allow the continuous completion of the mantle masonry of which always parts were covered by the ramps and did not allow works as long as the transport track was open. Since the ramps rested on the side of the building, the transport delivery could always take place at the height of the current work, while the construction of the extension section was in progress in the extension of the ramp route. Once this was completed, the transfer point to the building was moved accordingly. After that, the area of the sloping paneling, which was interrupted by the transport flow, could be completed so that no real breach was created.

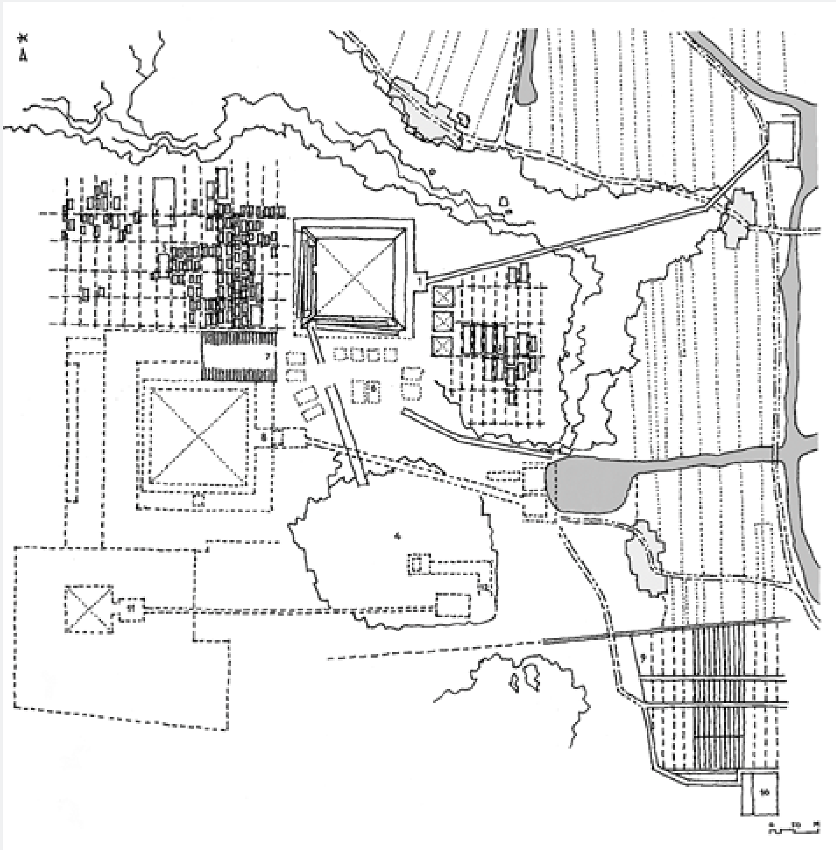

Figure 17: Giza, Pyramid District at the time of the Khufu Pyramid under construction.

1. Khufu Pyramid with ascent and valley temple
2. Eastern burial ground
3. Western burial ground
4. Quarry
5. Mastaba of Hemiunu
6. Building material depots
7. Workshops and magazines (presumed)
8. Later Khafrê Pyramid with mortuary temple, ascent, valley and sphinx temple
9. Southern quarters with gallery buildings
10. Royal Administration Building
11. Later Pyramid of Menkaure
12. Later mastaba of Khentkaus

grey: water; light grey: old villages; dotted lines: later pyramids

[71]Stadelmann 1991, p. 225
[72]Lehner 2017, p. 417
[73]Goyon 1977, p. 149

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The possible dimensions of the ramp ultimately result from the geometry of the pyramid itself. The assumed gradient of 10%, which can be managed by rope teams of 10 men with stones of one to two tons, and the side dimensions that decrease upwards of the pyramid result into a decreased width towards the top. It is obvious to start with three standardized ramp widths, which accommodated both building practice and the ancient Egyptian trend towards convention. Special widths of 7 m or more could be used at the base, which made maneuvering easier and helped to avoid blockages; oxen teams could also work here. At middle heights, a ramp of 5 m or ten cubits was the general standard measure. From the 12th ramp it was possible to reduce to 3.5 m (7 cubits) (Figure 16); this only affected around ten percent of the stone mass to be transported and a significantly reduced transport tact, as the area to be built was much smaller here and thus the number of people working at the same time, too (while in the same time more people were needed for transport).

Some authors therefore assume that in the area of the pyramid summit only stone steps were practicable, over which the stones were heaved with the help of wooden levers[71]. Lehner found in his NOVA experiment that this lifting technique was very exhausting and very cumbersome[72], which would have slowed down the work cycle considerably. From this it follows that the lever technique, which is undoubtedly used in various ways for high-altitude transport, can only be assumed for exceptional cases.

It is therefore likely that ramps led to the top. At a height of 103 m, a good two thirds of the pyramid height and more than 90 percent of the volume were built up; but the rest of the construction, especially at a height of more than 100 m above the ground, remained a huge challenge. Nevertheless, a ramp width of 3.5 m was practicable, and Goyon generally regards this as a sufficient width for train crews[73].

The claim made here is definitely not that the hypothesis presented corresponds in every detail to the historical events, especially on every single pyramid construction site. Instead of searching for a thoroughly constructed and calculated ramp hypothesis that seeks to explain the entire pyramid building program, future research could rather crystallize a bunch of possible working methods that offer possible “from - to” variants. The study presented here aims to make a contribution to this. The ethno-archaeological approach that has been included here is an important corrective that can bring the logic of the theory to some extent into line with the practical experience of comparable living environments.

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