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Fundamental considerations and findings on the construction of the pyramids in the Old Kingdom

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Fundamental considerations and findings on the construction of the pyramids in the Old Kingdom

In the past, many hypotheses about the construction of the pyramids in ancient Egypt were put forward by renowned Egyptologists, engineers and architects. In this article, fundamental considerations and findings on pyramid construction are explained. Subsequently, a proposal for the construction of the pyramids in the Old Kingdom is presented, based on these considerations.

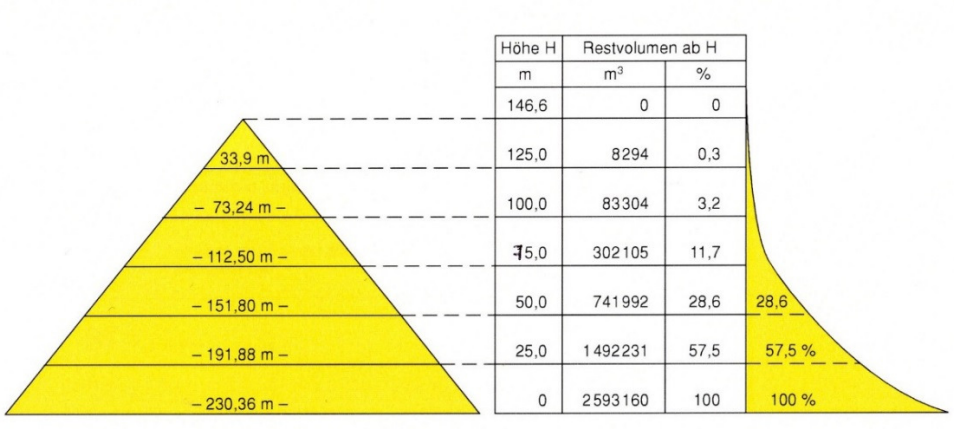
1. Introduction

The average life expectancy of people in Ancient Egypt was about 35 years. Despite the high standard of human medicine, many inflammations were fatal, especially after injuries. Even under above-average hygienic living conditions and with excellent medical care and the best nutrition, kings and high officials were affected by unexpectedly occurring diseases with fatal results.

Of the 22 kings of the 3rd to 6th dynasty to whom pyramids could be attributed, at least six died before the completion of their tombs: Sekhemkhet, Khaba, Djedefre, Bikheris, Shepseskare and Neferefre.[1] Every king therefore probably ordered at the beginning of his reign to finish his tomb in the shortest possible time. This order then also determined the building process. The top priority was therefore the minimum time for the completion of the planned pyramid.

2. Fundamental statements

As can be seen in Fig.1, using the volume of the Pyramid of Khufu as an example, about 70% of the building material is used in the lower third: At a height of 50 m the remaining stone volume is 28.6%.[2]



Höhe H	Restvolumen ab H	
m	m³	%
146,6	0	0
125,0	8294	0,3
100,0	83304	3,2
75,0	302105	11,7
50,0	741992	28,6
25,0	1492231	57,5
0	2593160	100

Fig.1

[1] Müller-Römer, F. Der Bau der Pyramiden im Alten Ägypten, Utz Verlag, München 2011, p.35ff.
[2] [2] Lattermann, W., Der Bau der Cheopspyramide, Eigenverlag, München 2002, p.32.

The transport of building material along only one ramp (Fig.2) always requires more time than the transport over several ramps.

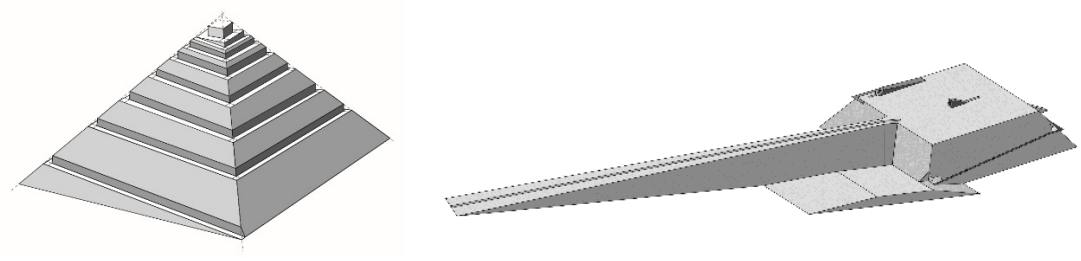


Fig.2

For space reasons, most pyramids can only be built with ramps parallel to the sides. The transport capacity of several tangentially arranged ramps significantly reduces the construction time (Fig.3). The transport capacity of the tangentially positioned ramps is essential for the building time.

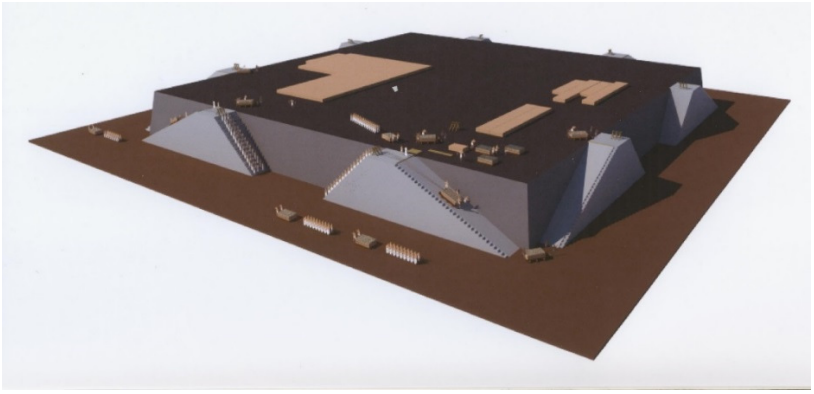


Fig.3

This leads to **conclusion 1**: A minimum construction time of the pyramid can only be achieved by building on all four sides simultaneously.

Stone storage next to the pyramid was out of the question on many construction sites due to lack of space. Lifting devices for stacking are not documented archaeologically in the Old Kingdom.

This leads to **conclusion 2**: The production of the stones, the transport to the building site and the construction of the pyramid itself had to be carried out in a coordinated manner ("just in time").

The daily required quantities of stone could be produced in parallel in different quarries. This was proven at the construction sites for the Red Pyramid and for the Pyramid of Khufu. The transport from the quarries to the construction site could also take place simultaneously via several ramps. Therefore the time needed for the transport via the tangentially arranged ramps during the construction of the pyramid was the decisive factor for the construction time of the pyramid.

The horizontal shifting and the installation of the stones in the uppermost layer of the pyramid truncation (Fig.3) could be carried out by a large number of workers at the same time. Both work processes were only dependent on the amount of stones pulled up the ramps and were therefore not decisive for the construction time.

Stone transport over the longer ramps from the quarries to the construction site also had to be possible with breaks for the draught animals or draught teams. The gradients therefore had to

be dimensioned in such a way that backward slipping was avoided. The static friction $R = \mu \cdot Q \cdot \cos \alpha$ must always be greater than the force $Q \cdot \sin \alpha$, which pulls the load down the valley (Fig.4):

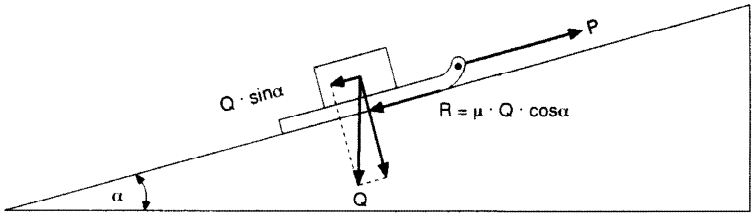


Fig.4

Conclusion 3 therefore states: Transport ramps from the quarries to the construction site must only have a maximum gradient of 7 - 8%. These gradients are archaeologically proven.

Conclusion 4: In contrast, the tangential ramps arranged on the four sides of the pyramid can be built much steeper because of the short pulling distances (Fig.3). Breaks are not necessary.

3. Development of construction methods for the pyramids of the Old Kingdom

The pyramids of Djoser and Sekhemkhet in Sakkara North, those of Khaba in Zawyet El Aryan and those of Seneferu in Meidum and Dahshur South consist of stone layers leaning against an inner core (Fig.5). In modern literature they are called layered pyramids.

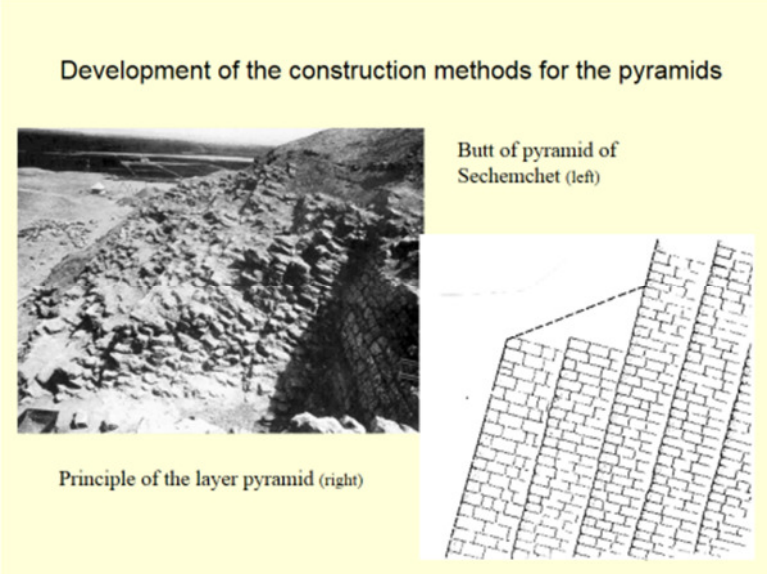


Fig.5

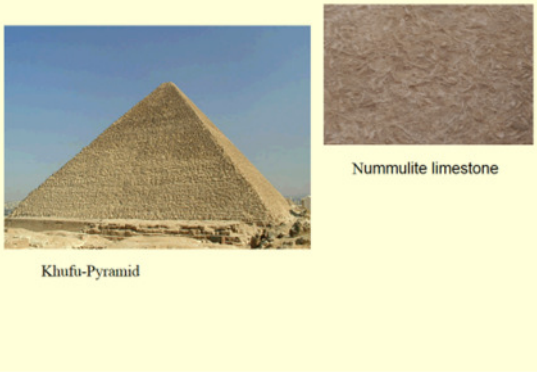
In Egypt earthquakes repeatedly caused damage to the pyramids. The pyramids of Seneferu in Meidum and in Dahshur South and North were partially heavily damaged. The high ground pressure of the pyramids and the partly unsafe ground also contributed to the damage. The weight of the pyramids per m² is far above that of modern buildings.

Therefore, the master builders of Seneferu decided to lay the stones horizontally in the upper part of the fold pyramid, when building the cult pyramid next to the Bent pyramid and when building the Red Pyramid. In addition, for the Red Pyramid the offset was reduced to 28 fingers per cubit, i.e. to an angle of 45° (Fig.6).

Red Pyramid Dashur North

Fig.6

During the construction of the Pyramid of Khufu another change was made: The very stable nummulite limestone (Fig.7) plateau near Gisa was chosen as building site. The pyramid was built in a core step structure. At the same time the outer casing stones was applied. This is the result of investigations by various Egyptologists and the author as well as measurements taken in 2007 at the pyramid of Khufu with the consent of the Egyptian Minister of Antiquities.[3]



Khufu-Pyramid

Fig.7

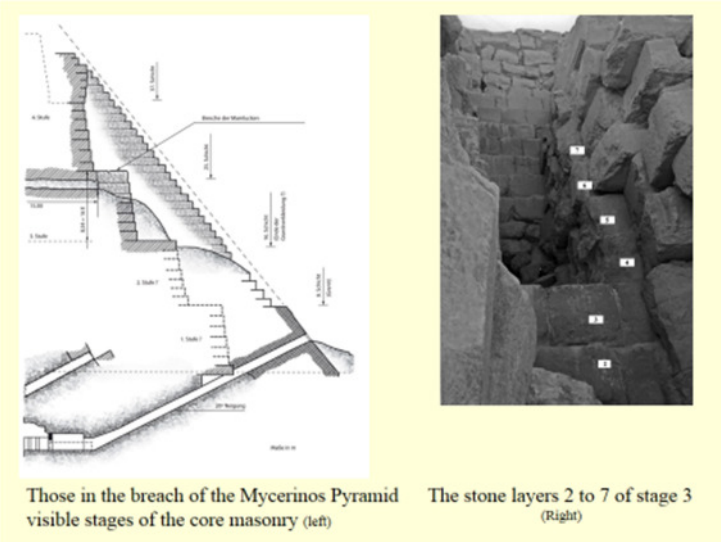
This core step structure is clearly visible at the pyramid of Menkaure (Mykerinos) in its up to 8 m deep breach on the northern side, which the Mamlukes have struck while searching for the entrance (Fig.8).

Pyramid of Menkaure

Fig.8

[3] Müller-Römer, F. Der Bau der Pyramiden im Alten Ägypten, Utz Verlag, München 2011, p.174ff.; Vyse, H., Operations carried out on the Pyramids of Gizeh; Stadelmann, R., Die ägyptischen Pyramiden, Verlag von Zabern, 3rd. Edition 1997, p.109; Isler, M., Sticks, stones & Shadows, University of Oklahoma Press, 2001, p.201.

Maragioglio and Rinaldi have made a cross-sectional drawing of this breach. The second, third and fourth stages of the internal structure are clearly visible (Fig.9 left).[4]



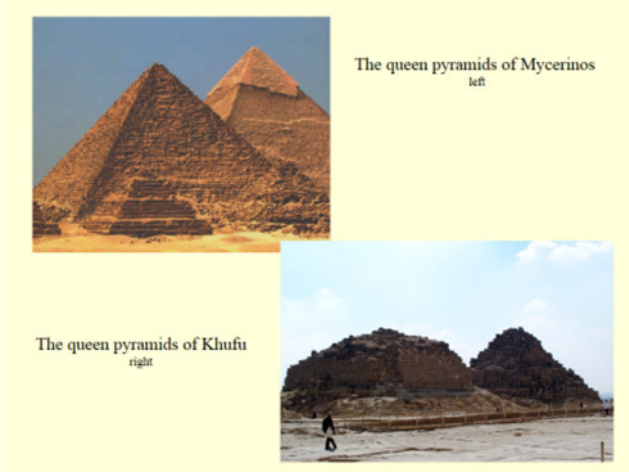
Those in the breach of the Mycerinos Pyramid visible stages of the core masonry (left)

The stone layers 2 to 7 of stage 3 (Right)

Fig.9

The interior of the pyramid consists of superimposed rectangular "stone boxes", similar to Mastaba, whose ground plan becomes smaller towards the top. The outer walls, which are slightly inclined inwards, are made of precisely hewn stones. Stones of different sizes are used inside. The spaces in between were filled with sand and Tafla (loam) to distribute the pressure evenly. The advantage of this construction method is also that earth shocks can be absorbed much more elastically than with masonry made of precisely cut stones. In addition, the majority of the stones do not have to be finished. This construction method leads to a minimization of costs.

The queen pyramids of Khufu and Menkaure also clearly show the core step structures (Fig.10).



The queen pyramids of Mycerinos left

The queen pyramids of Khufu right

Fig.10

The construction method of the core step structure and the outer cladding of the pyramids was maintained until the end of the 6th dynasty and is archaeologically proven (Fig.11, Pyramid of Neferirkare in Abusir).

[4] [4] Maragioglio, V. und Rinaldi, C. A., L'Architettura delle Piramidi Menfite, Vol. VI, p.34ff. and Addenda, TAV. 4, fig..2, section drawing S-N, edited by Müller-Römer.

Fig.11

The **conclusion 5** is therefore: The pyramids of the 4th to 6th dynasty were built as step pyramids with an outer casing from the construction of the pyramid of Khufu onwards. In modern literature this term is increasingly used.

This is followed by **conclusion 6**: The construction of the outer cladding of the pyramids, the putting on of the pyramidion and the smoothing of the cacing stones from top to bottom can for constructional reasons only be carried out when using platforms or scaffolds mounted outside.

4. Measurement technology

Measurement technology was particularly important in the construction of the pyramids. The four corner edges were always to be guided upwards in a straight line and at the same angle. At the top they had to meet at one point. Between them flat surfaces had to be built. This required levelling and height measurement, angle measurement and length measurement, each with great accuracy (Fig.12).

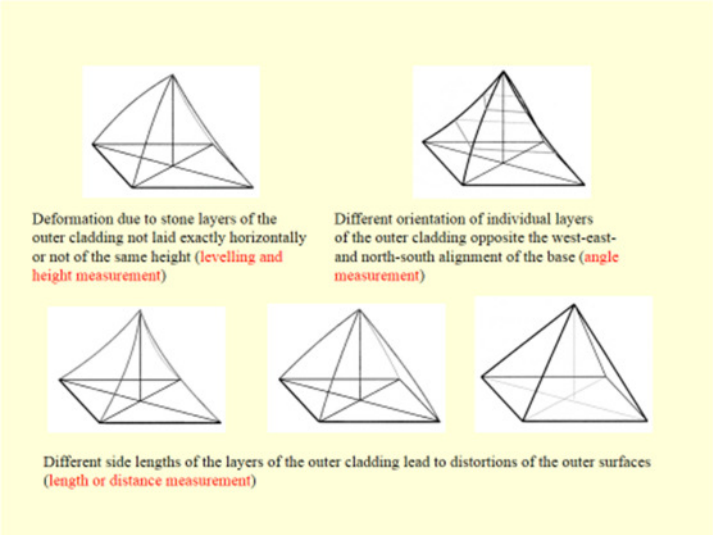


Fig.12

The height of a step of the core masonry and the simultaneously built cladding layers and casing stones could be determined with a measuring rod from the length of the corner edge and the offset (“seked”, horizontal displacement inwards). Minor corrections were thus possible. A diagonal measurement between the four corners was also possible. Thus a constant comparison was possible. A central plumb bob was not necessary. The guidance of the corner edges of a step in a straight line could be checked by means of a longer measuring rod. In order to be able to carry out the measurements, the exact laying of the cornerstones was necessary.

5. Tools

The **7th conclusion** is: Hypotheses on the construction of the pyramids in the Old Kingdom may only include tools, aids and procedures for material extraction and transport that are archaeologically proven. These include copper chisels, stone balls, wooden beams as levers, transport sledges, inclined planes as well as ramps, rollers, ropes and deflection devices (Fig.13).

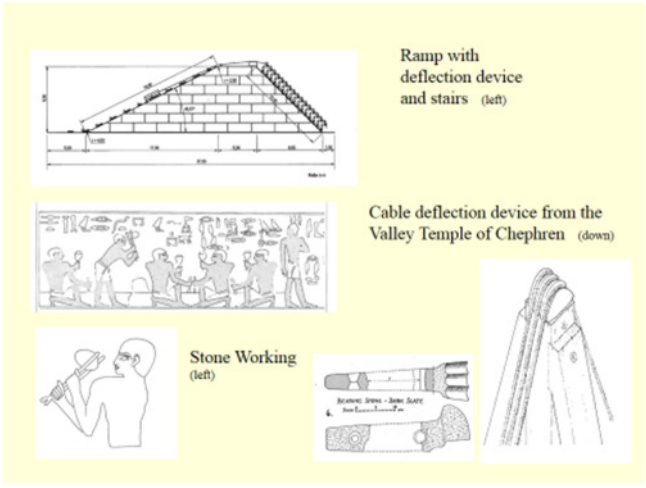


Fig.13

Short steep ramps with a recess of 1 (height) to 2 (base), which corresponds to an angle of 24.5°, are archaeologically documented several times in the Old Kingdom: At entrances to burial chambers of pyramids and in illustrations in private graves (Fig.14).

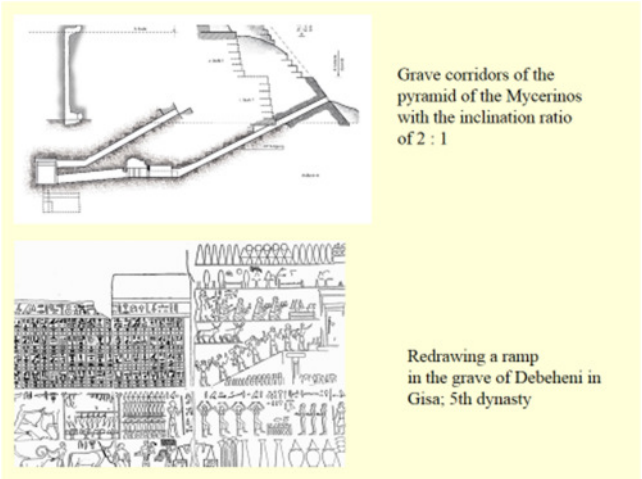


Fig.14

The **seven conclusions** define the essential conditions for the construction of pyramids in the Old Kingdom.

6. Evaluation of the most important building hypotheses published so far

The building hypotheses published so far by Egyptologists such as Arnold, Lauer and Stadelmann are based on ramps leading vertically to the pyramid. These have a lower transport capacity compared to tangential ramps. The construction of the ramps requires partly a considerable amount of building material and a large area. The shortest possible construction time cannot be achieved with these proposals. Suggestions for solutions for setting up the pyramidion and smoothing the outer surfaces are not made (Fig.15).

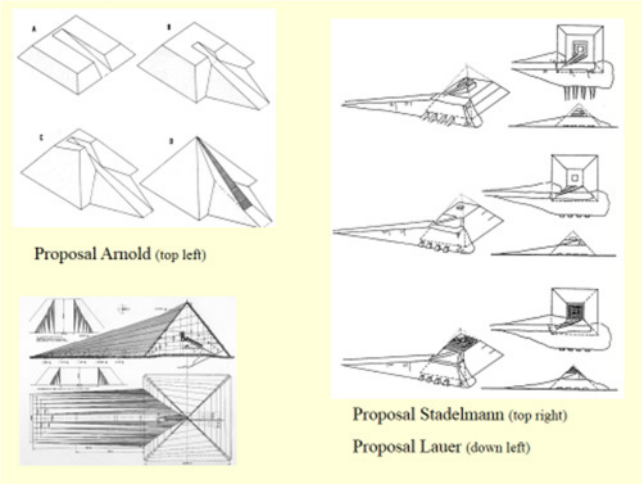


Fig.15

The same applies to building hypotheses proposed by Goyon, Lehner and Klemm, among others, with a ramp arranged spirally around the pyramid stump (Fig.16).

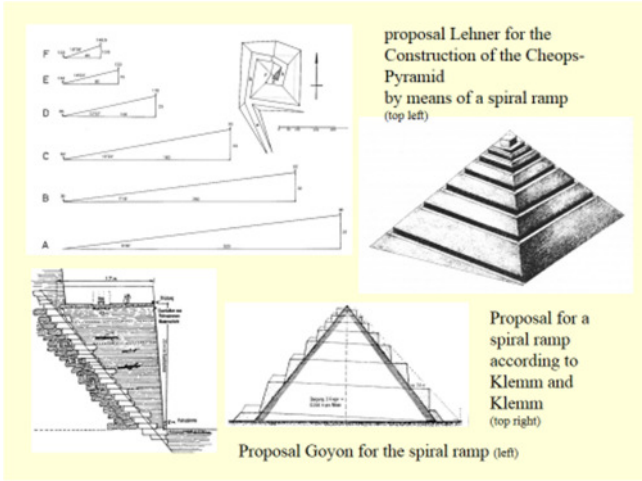


Fig.16

Other building hypotheses such as those of Haan, Houdin, Isler and Kerres are also ruled out for a number of reasons (Fig.17).

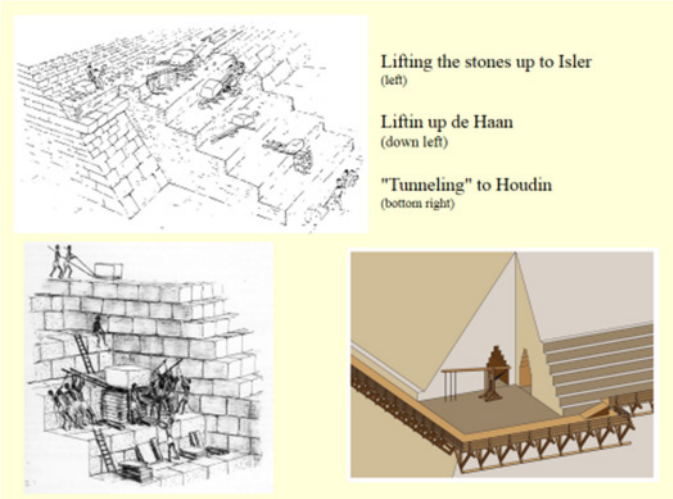


Fig.17

Most of the hypotheses on pyramid construction presented so far also do not provide a conclusive solution for placing the pyramidion and smoothing the casing stones of the pyramid from top to bottom. Also calculations of the construction time are missing in most suggestions.

Furthermore, the building hypotheses presented by non-Egyptologists very often neglect the archaeological evidence of building methods and tools in the Old Empire, as formulated in conclusion 7.

7. The author's theory on the construction of the pyramids in the Old Kingdom

The different construction phases

The individual construction phases of the proposal for the construction of the cased step pyramids using steep ramps tangentially attached to the sides and conversions are shown in principle using the example of the pyramid of Menkaure (Fig.18): At the same time as the steps of the core structure (dark brown) are built, the outer cladding layer (yellow) is erected. In order to illustrate this construction method, the core step structure was extended upwards in Fig. 18. Platforms for the construction of the tangential ramps and the transport of the building materials are attached to the outer, not yet smoothed casing stones (bosses) at the same height as the core steps (grey).

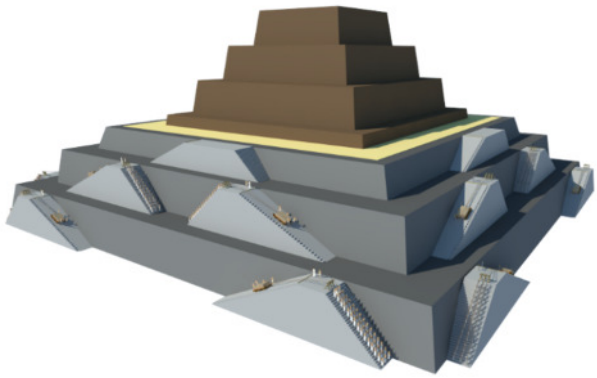


Fig.18

Fig. 19 shows the finished pyramid with the outer platform. This also encloses the top of the pyramid and thus allows the pyramidion to be put up without any problems (Fig.20).

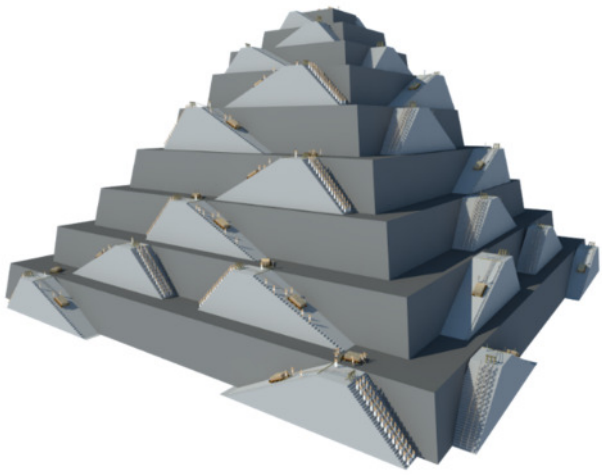


Fig.19

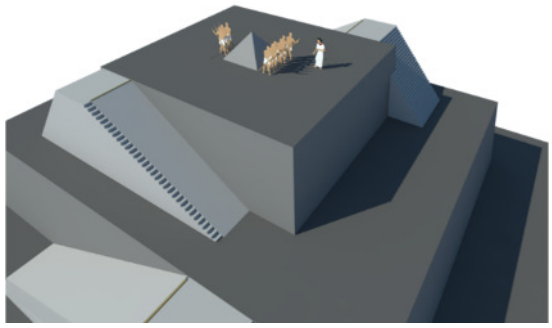


Fig.20

Once the pyramidion is in place, the outer platforms are then removed from top to bottom while smoothing the casing stones. The workers stand on the steps of the platforms and can carry out the work without danger (Fig.21).

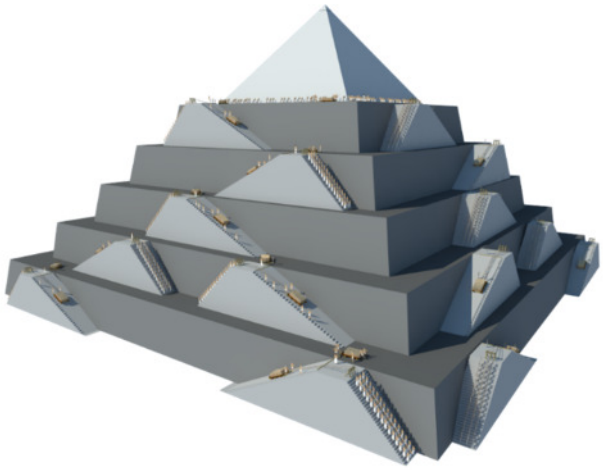


Fig.21

Calculation of the construction time

Various assumptions are made for the calculation of the construction time: The average stone size is assumed to be 1.2 m³ and the weight per towing operation 3 t. The cycle time for a towing operation of one stone to the platform of the ramp (Fig.22) is assumed to be 15 minutes and a daily working time of 10 hours in shift operation on 300 days a year. The assumed dimensions of the ramps and step height are shown in Fig. 22. With a downward pulling weight of a worker of 75 kg approx. 20 workers are required.

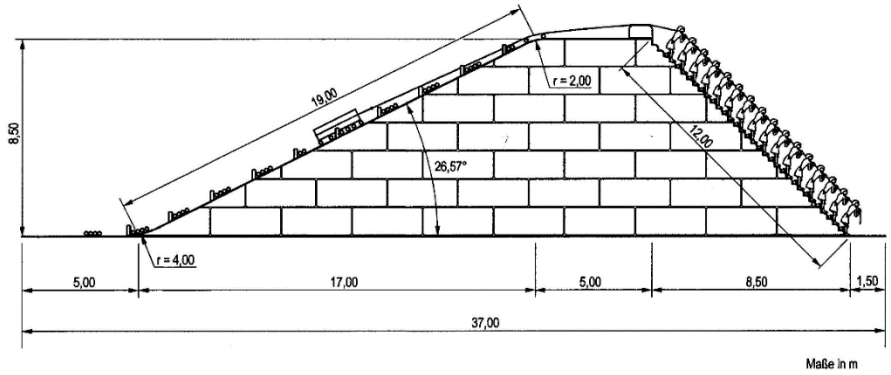


Fig.22

In the spring of 2012, the author showed during a television production of the ZDF[5] that a stone weighing approx. 1.5 t could be pulled upwards on a ramp of approx. 10° by a pulling team consisting of 12 - 14 persons without too much effort (Fig.23).

Fig.23

The cycle time of 15 minutes, which was previously set on the basis of considerations with civil engineers and the results of the tensile test of the test described above, could unfortunately not yet be verified on a model (Fig. 22). However, the actual construction time of the pyramid is largely determined by this. An application to the German Research Foundation (DFG) for financing a practical test in 2014 was submitted, but unfortunately rejected.

The construction time for the core masonry, the cladding masonry and its smoothing, the construction and dismantling of the ramps and the outer platforms as well as for the preparatory measures for the construction of the pyramid of the Menkaure will take about 4.8 years according to the described procedure. A comparative calculation using the same construction method for the Pyramid of Khufu and the Red Pyramid results in construction times of 22.5 and 18.7 years respectively. The construction of the Red Pyramid is assumed to start in the 15th year of the reign of Seneferu.

The calculated construction times of the three pyramids do not therefore contradict the reigns of the kings: Seneferu 35 years, Khufu 23 years and Menkaure - more recently 6 years (after Kauss and Warburton).[6]

Concluding remark

The author's proposal described above for the construction of the pyramids in the Old Kingdom by means of tangentially arranged steep ramps and an external platform was first published in 2008. In a further publication[7] as well as in various publications a supplemented and further developed version of the theory for the construction of the pyramids in the Old Kingdom was presented.

Pictures and drawings: Frank Müller-Römer frank-mueller-roemer@t-online.de

[5] Series pur+ "The largest grave in the world", 16.6.2012, ZDF.
[6] Hornung, E., Krauss, R., Warnurton, D., A., ed., Ancient Egyptian Chronology, HdO. Section 1, Vol. 83, Brill, Leiden 2006, S.485.
[7] Müller-Römer, F. Der Bau der Pyramiden im Alten Ägypten, Utz Verlag, München 2011.